SCIENCE AND INDUSTRY
MAR 25 1943
ANGELES PUBLIC LIBRARY
STACKS

VOLUME LI NUMBER 2

THE JOURNAL of GEOLOGY

A SEMI-QUARTERLY

REFERENCE
DO NOT LOAN

EDITED BY
ROLLIN T. CHAMBERLIN

With the Active Collaboration of

EDSON S. BASTIN, Economic Geology
NORMAN L. BOWEN, Petrology
J HARLEN BRETZ, Geomorphology
CAREY CRONEIS, Invertebrate Paleontology
D. JEROME FISHER, Mineralogy
FRANCIS J. PETTIJOHN, Sedimentology
ALFRED S. ROMER, Vertebrate Paleontology

ASSOCIATE EDITORS

H. ALBERT BROUWER, The Netherlands
GERARD DeGEER, Sweden
ALBRECHT PENCK, Germany
*FRANK D. ADAMS, McGill University
WALLACE W. ATWOOD, Clark University
ARTHUR L. DAY, Carnegie Institution
WILLIAM H. EMMONS, University of Minnesota
WILLIAM H. HOBBS, University of Michigan
CHARLES K. LEITH, University of Wisconsin
ELWOOD S. MOORE, University of Toronto
JOHN B. REESIDE, Jr., U.S. Geological Survey
BAILEY WILLIS, Stanford University

*Deceased

FEBRUARY-MARCH 1943

SHEET STRUCTURE IN GRANITES: ITS ORIGIN AND USE AS A MEASURE OF GLACIAL EROSION IN NEW ENGLAND - - - - - - - - - - RICHARD H. JAHNS 71

THE RARER METALLIC CONSTITUENTS OF SOME AMERICAN IGNEOUS ROCKS. I
ERNEST B. SANDELL AND SAMUEL S. GOLDICH 99

MAFIC AND ULTRAMAFIC ROCKS OF THE BAIE VERTE AREA, NEWFOUNDLAND
KENNETH DeP. WATSON 116

GLACIATION OF THE DU NOIR VALLEY, FREMONT COUNTY, WYOMING
NEIL A. MINER AND DAVID M. DELO 131

REVIEWS

The Origin of the Carolina Bays, DOUGLAS JOHNSON (J. Hoover Mackin) - - - - - - - 138

The Dynamics of Faulting and Dyke Formation with Application to Britain, E. M. ANDERSON (R. T. C.) - 140

"Laterite and Its Structural Uses in Thailand and Cambodia," ROBERT L. PENDLETON; "Laterite, or Sila Laeng, a Peculiar Soil Formation," ROBERT L. PENDLETON; "Analyses and Profile Notes of Some Laterite Soils and Soils with Iron Concretions of Thailand," ROBERT L. PENDLETON AND SANGAR SHARASUVANA (A. O. Woodford) - - - - - - - - - - - - - - 140

Report of a Conference on Sedimentation (F. J. Pettijohn) - - - - - - - - - - - - 141

The Geology of Crater Lake National Park, Oregon, with a Reconnaissance of the Cascade Range Southward to Mount Shasta, HOWEL WILLIAMS (R. T. C.) - - - - - - - - - - - 142

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS, U.S.A.

February-March 1943 Vol. LI, No. 2

THE JOURNAL OF GEOLOGY

EDITED BY
ROLLIN T. CHAMBERLIN

With the Active Collaboration of

EDSON S. BASTIN
Economic Geology

CAREY CRONEIS
Invertebrate Paleontology

NORMAN L. BOWEN
Petrology

D. JEROME FISHER
Mineralogy

J HARLEN BRETZ
Geomorphology

FRANCIS J. PETTIJOHN
Sedimentology

ALFRED S. ROMER
Vertebrate Paleontology

The Journal of Geology is published by the University of Chicago at the University of Chicago Press, 5750 Ellis Avenue, Chicago, Illinois, semi-quarterly, on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 14. ¶ The subscription price is $6.00 per year, the price of single copies is $1.00. Orders for service of less than a full year will be charged at the single-copy rate. ¶ Postage is prepaid by the publishers on all orders from the United States and its possessions, Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, Guatemala, Haiti, Republic of Honduras, Mexico, Morocco (Spanish Zone), Nicaragua, Panama, Paraguay, Peru, Rio de Oro, El Salvador, Spain (including Balearic Islands, Canary Islands, and the Spanish Offices in Northern Africa; Andorra), Spanish Guinea, Uruguay, and Venezuela. ¶ Postage is charged extra as follows: for Canada and Newfoundland, 32 cents on annual subscriptions (total $6.32); on single copies 4 cents (total $1.04); for all other countries in the Postal Union 80 cents on annual subscriptions (total $6.80), on single copies 10 cents (total $1.10). ¶ Patrons are requested to make all remittances payable to The University of Chicago Press in United States currency or its equivalent by postal or express money orders or bank drafts.

The following are authorized agents:

For the British Empire, except North America, India, and Australasia: The Cambridge University Press, Bentley House, 200 Euston Road, London, N.W. 1. Prices of yearly subscriptions and of single copies may be had on application.

Claims for missing numbers should be made within the month following the regular month of publication. The publishers expect to supply missing numbers free only when losses have been sustained in transit, and when the reserve stock will permit.

Business correspondence should be addressed to The University of Chicago Press, Chicago, Ill.

Communications for the editors and manuscripts should be addressed to the Editor of THE JOURNAL OF GEOLOGY, The University of Chicago, Chicago, Ill.

Contributors are requested to write scientific and proper names with particular care and in citations to follow the form shown in the pages of the Journal.

Because of the high cost of printing, this Journal has found it necessary to adopt the following rules. ¶ 1. The cost of illustrative material, in excess of $1.50 per page for the article, beyond the cost of type which would have occupied the same space, shall be borne by the author. ¶ 2. The cost of excessive alterations (i.e., changes from the original manuscript) made by the author will be charged to him. ¶ 3. For the present the Journal will supply free 50 reprints (without covers) of each article. Additional reprints must be ordered in advance of publication; rates will be furnished on request.

The articles in this Journal are indexed in the *International Index to Periodicals*, New York, N.Y.

Applications for permission to quote from this Journal should be addressed to The University of Chicago Press, and will be freely granted.

Entered as second-class matter March 20, 1893, at the Post-office at Chicago, Ill., under the Act of March 3, 1879.
Acceptance for mailing at special rate of postage provided for in United States Postal Act of October 3, 1917, Section 1103, amended February 28, 1925, authorized July 15, 1918.

[PRINTED IN U.S.A.]

VOLUME LI NUMBER 2

THE JOURNAL OF GEOLOGY

February-March 1943

SHEET STRUCTURE IN GRANITES: ITS ORIGIN AND USE AS A MEASURE OF GLACIAL EROSION IN NEW ENGLAND[1]

RICHARD H. JAHNS
United States Department of the Interior, Geological Survey

ABSTRACT

Sheet structure in New England granites tends toward parallelism with the exposed rock surface and is completely independent of all primary rock structures, commonly transecting contacts between the granite and xenoliths, roof pendants, the country rock itself, and minor postgranite intrusive bodies. In general the sheets become progressively thicker, flatter, and more regular with increasing depth. Evaluation of the possible causes of the structure indicates that relief, through removal of superincumbent load, of a primary confining pressure is chiefly responsible for the large-scale exfoliation phenomena involved. Insolation, the progressive hydration and formation of chemical alteration products in certain susceptible minerals, and the mechanical action of fire, frost, and vegetation are possible minor contributory causes.

With insignificant exceptions, sheeting in northeastern Massachusetts and adjacent parts of New Hampshire, where detailed studies have been made, is preglacial in origin. Its attitude with respect to present topography therefore facilitates certain comparisons with preglacial topography and thus permits minimum estimates of the thickness of material removed by glacial ice from specific localities. Not only do the granite sheets or shells thicken with depth, but statistical data demonstrate a fair degree of quantitative consistency in this relation. The sizes of large granite boulders—and therefore of the respective sheets from which they were torn—thus furnish an additional clue to their original depth beneath the preglacial surface. Results of these studies suggest the removal of a blanket of rock and preglacial regolith at least 10–15 feet thick by glacial abrasion and plucking from the stoss, or north, slopes of most hills, and of a somewhat greater thickness from their east slopes, summits, and west slopes. Severe plucking and quarrying of the rock appears to have been responsible for strongly concentrated erosion on the lee, or south and southeast slopes of many hills to maximum demonstrable depths in excess of 100 feet.

INTRODUCTION

Sheet structure, or large-scale exfoliation, has long been recognized as one of the most prominent features of many New England granites. It has been described by T. N. Dale[2] as "the division of granite into 'sheets' or 'beds' by jointlike fractures which are variously curved or nearly horizontal, being generally parallel with the granite surface." This concentric layering is unusually well shown on many hills in northeastern Massachusetts and adjacent parts of southern New Hampshire, where the attitude and curvature of the sheet fractures tend toward close conformity with the exposed surface of the granite.

This conformable relation between sheeting and bedrock topography is generally consistent over most parts of an individual hill, but in some places, particularly on south slopes, a marked discordance appears. The hill slope in these

[1] Published by permission of the director of the Geological Survey, U.S. Department of the Interior, Washington, D.C., and the commissioner of public works, Commonwealth of Massachusetts, Boston, Massachusetts.

[2] "The Commercial Granites of New England," *U.S. Geol. Surv. Bull. 738* (1923), p. 26.

places ordinarily dips more steeply than the sheet structure. It is a common assertion among quarrymen, for example, that such granite hills "open toward the south," or that the exposed "raw" edges of the granite sheets usually appear on south slopes only. Even a preliminary examination suffices to show that this is due not to marked changes in the attitude of the sheet structure but to an appreciable oversteepening of the south slopes of such hills. Such selective oversteepening of bedrock hills has generally been ascribed by students of New England geology to glacial erosion, chiefly plucking.

The writer has had opportunity to examine in detail many of the granite hills between Fitchburg and Lowell, Massachusetts, and several others in the vicinity of Milford, New Hampshire (see Fig. 1). It became increasingly evident during the course of these examinations that the present characteristics of sheet structure and the type and amount of glacial erosion on any one hill are closely and consistently related. Since little quantitative information concerning the amount of erosion accomplished by continental ice sheets is yet available, it has seemed desirable to record and evaluate all obtainable data bearing on this inter-

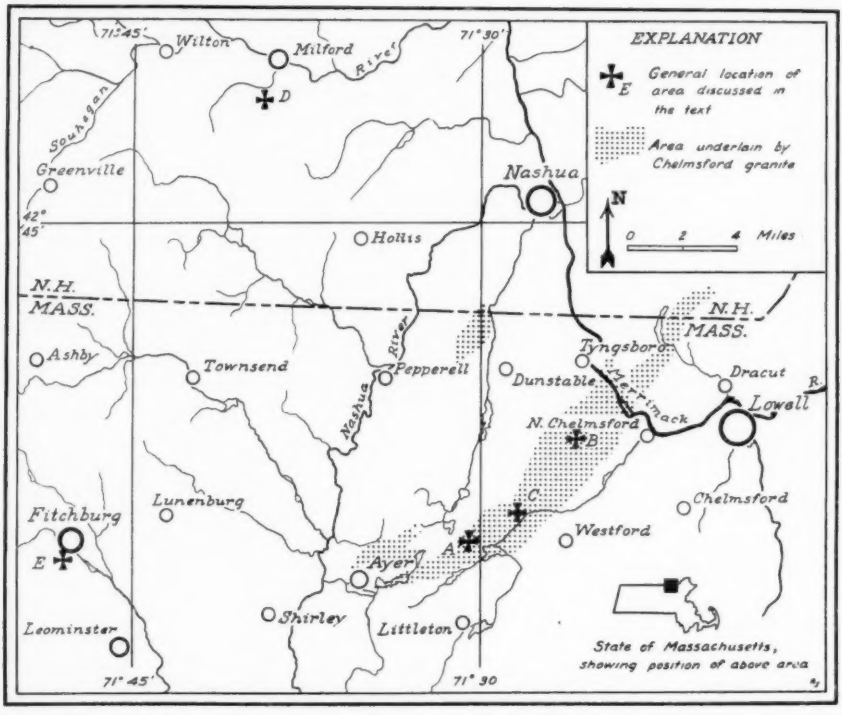

FIG. 1.—Index map of a part of northeastern Massachusetts and southern New Hampshire. Localities discussed specifically in the text are marked by crosses as follows: *A*, Fletcher Hill and vicinity; *B*, Oak Hill and vicinity; *C*, Snake Meadow Hill; *D*, Kittredge Hill; *E*, Rollstone Hill.

esting problem in the areas studied. Some understanding of the probable origin and significance of sheet structure (or exfoliation) is an essential prelude to any evaluation of the data; hence the first part of this paper is devoted to a discussion of the structure itself. Next, the effect of glacial erosion on sheet structure is treated in the light of several representative examples; and, finally, statistical data are presented in support of the tentative quantitative conclusions advanced.

FIELD WORK

All field work in Massachusetts was done under the joint auspices of the Geological Survey, United States Department of the Interior, and the Department of Public Works, Commonwealth of Massachusetts, during the seasons 1939–41. The studies near Milford, New Hampshire, were made in 1937, when the writer served as assistant to L. W. Currier during investigations of the granite quarries in that district. Critical points were revisited in July, 1940.

SHEET STRUCTURE IN GRANITES

CHARACTERISTIC FEATURES

Throughout this paper the term "granite" is used in its broad commercial sense and therefore includes in the different areas discussed those rock types scientifically designated as granite, granite gneiss, and quartz monzonite. Not only are the general features of sheet structure similar in these three types, but they also appear to be characteristic of anorthosites, most of the more granitic paragneisses, and nearly all intrusive rocks of silicic and intermediate composition. Exfoliation domes, on which the sheet or exfoliation structure dips quaquaversally, have been recognized in various terranes in both glaciated and nonglaciated regions,[3] and most reports on commercial granites[4] contain numerous descriptions of the structure.

The flat to gently curved fractures, "seams," or partings that separate a granite into thin lenses and tabular masses ("beds" or sheets) are most conspicuously developed near the surface of the rock, where they generally conform to topography. With increasing depth the sheets tend to become progressively thicker, more nearly horizontal, and less irregular (Figs. 2, 3, 6, 12, 15). Their rate of thickening and the perfection of their development vary markedly in different rocks and may vary within certain limits from place to place in a single igneous mass. As seen in many quarries in the areas under consideration, individual sheets within 15–35 feet of the surface are generally thin, elongated lenses with irregular edges. They vary in thickness from knife edges to several feet and normally are so arranged that the thickest part of one sheet is overlain and underlain by relatively thin parts of the immediately adjacent sheets (Figs. 2, 3, 6).

Most of the intersheet fractures (or exfoliation planes), if traced far enough, can be seen to merge with adjacent fractures; others fade gradually in intensity and disappear, so that two sheets unite to

[3] See, for example: H. W. Turner, "The Pleistocene Geology of the South-central Sierra Nevada, with Especial Reference to the Origin of the Yosemite Valley," *Proc. Calif. Acad. Sci.*, Vol. I: *Geology* (3d ser., 1900), pp. 312–14, Pl. XXXVII; G. K. Gilbert, "Domes and Dome Structure of the High Sierras," *Bull. Geol. Soc. Amer.*, Vol. XV (1904), pp. 29–36, Pl. III; T. L. Watson, "Granites of the Southeastern Atlantic States," *U.S. Geol. Surv. Bull. 426* (1910); W. J. Miller, "Exfoliation Domes in Warren County, New York," *New York State Mus. Bull. 149* (1911), pp. 187–94; F. E. Matthes, "Geological History of the Yosemite Valley," *U.S. Geol. Surv. Prof. Paper 160* (1930), pp. 114–17; Robert Balk, "Disintegration of Glaciated Cliffs," *Jour. Geomorph.*, Vol. II (1939), pp. 306–12.

[4] See, e.g., Watson, *op. cit.*, and Dale, *op. cit.*

FIG. 2.—Typical sheet structure in granite, north end of Upper Swenson quarry, Concord, New Hampshire. Sheet fractures are intersected by steeply dipping joints. Photograph by L. W. Currier.

FIG. 3.—Sheet structure in Chelmsford granite, southwest end of H. E. Fletcher quarry, Westford, Massachusetts. Note thin upper sheets. Several sheet fractures die out in foreground, thus uniting two or more sheets into single, much larger ones. Note strong mineralogic banding in the granite at extreme right.

form a single, much larger one (Fig. 3). Still others die out abruptly against much older, more steeply dipping joints, faults, or shear zones (Figs. 2, 4, 6) instead of passing through them with little or no change It is emphasized that a clear-cut distinction exists between sheet fractures (or exfoliation planes) and joints, faults, and similar features formed during the consolidation of the rock or as a result of tectonic activity after its consolidation. F. E. Matthes,[5] in his long-continued studies of geomorphic features in the Sierra Nevada, has noted that exfoliation is well developed in massive, joint-free rocks only and that it is absent entirely from those rocks that are moderately to heavily jointed. A strikingly similar relation exists in the New England granites, where the most sparsely jointed parts of a given rock mass possess the greatest number of sheet fractures.

The characteristic quaquaversal dips of sheeting on most granite hills are completely independent of all primary structures within the rock itself. This has been repeatedly stressed by Balk[6] in his observations on exfoliation in the Adirondack Mountains and in western New England. Countless quarry exposures in northeastern Massachusetts and southern New Hampshire show intersections between sheeting planes, on one hand, and foliation planes and mineralogic layering, on the other, that vary in angle from 1° to 90°. The older, more primary structures tend to maintain a rather uniform orientation, whereas the younger sheet structure is generally parallel with the present rock surface. This is not readily reconcilable with the suggestions of J. D. Whitney[7] and J. H. L. Vogt[8] that the attitude of sheeting conforms to the original shape of the intrusion. That no such genetic relation exists is further demonstrated by the random transection of roof pendants, xenoliths, late minor intrusive bodies (including pegmatite and aplite dikes), and even of the contacts of the main intrusive itself by the sheet fractures (Figs. 5, 6). Examples of the angular discordance between sheeting and older rock structures are shown

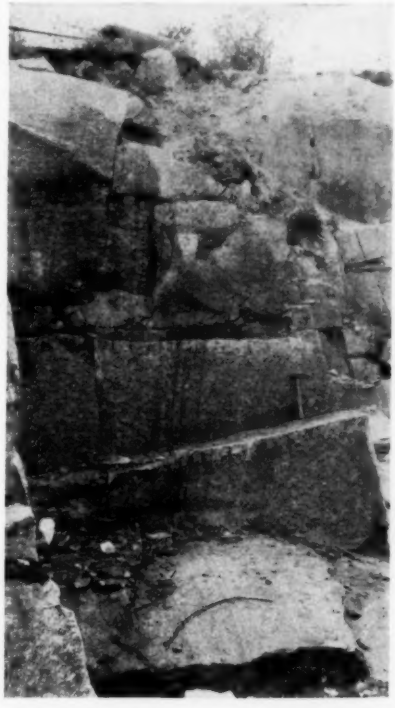

FIG. 4.—Sheet structure transecting strong mineralogic banding in Chelmsford granite. Small quarry west of Forge Village, Massachusetts. Foliation in the granite cuts the banding at distinct angles. Trace of foliation lies parallel to hammer handle.

[5] Oral communication, 1942.

[6] *Op. cit.*, pp. 306–12.

[7] *Geology of California*, Vol. I (1865), pp. 227, 372, 417.

[8] "Sheets of Granite and Syenite in their Relation to the Present Surface," *Geol. fören. i Stockholm förhandl.*, No. 56, Vol. IV (1879).

FIG. 5.—Granite with xenoliths of injection gneiss, northeast face of Palm and Koleh quarry, Milford, New Hampshire. Sheet fractures pass through both rocks but are less regular in the gneiss. Photograph by L. W. Currier.

FIG. 6.—Typical sheet structure in medium-grained granite, Kittredge quarry, Milford, New Hampshire. Note that sheet fractures are little affected by dike of fine-grained granite in left and center foreground. Photograph by L. W. Currier.

in Figures 8, 10, and 13 and are discussed further on. Several excellent examples of the transection of igneous contacts by sheet structure appear in the following quarries:

1. Rafferty quarry (ESE. of Cow Pond at edge of Ayer quadrangle, Massachusetts): The north quarry opening shows several large xenoliths and roof pendants of coarse, porphyritic biotite-granite gneiss in a finer, gneissic binary granite. Thin pegmatite dikes cut both rocks. On the west face of the south opening, an intricate contact zone between the granite and gneiss is well exposed. Sheet structure, which dips 9°–25° east and east-northeast, passes through both rock types but is slightly less regular in the gneiss. Foliation in the granite lies N. 15°–28° E., dip 85° E. to 85° W.

2. Ward quarry (0.5 mile west of Flushing Hill, Tyngsboro quadrangle, Massachusetts): An intricate contact zone involving gneissic binary granite; a fine-grained, faintly gneissic granite; coarse, porphyritic gneissic biotite granite; and thin pegmatite dikes is exposed on the west quarry wall and is there transected by sheet structure that dips moderately to the northeast. Foliation in the rocks has a general N. 35° E. strike and dips 85° SE.

3. Quarry on east side of Oak Hill (0.6 mile north of H. E. Fletcher quarry, Tyngsboro quadrangle, Massachusetts): A gneissic binary granite contains a large xenolith of coarse, porphyritic, gneissic biotite granite. Both rocks are cut by sheet fractures that dip gently to the east and southeast. Foliation of rocks: N. 38°–40° E., dip 85° SE.

4. Tonella Old quarry (1.6 miles south of Milford, Milford quadrangle, New Hampshire): Contacts between a fine-grained biotite granite and coarse, granitic injection gneiss are exposed on the west, south, and southeast quarry walls and are crossed by flat to very gently dipping sheet fractures.

5. Tonella King quarry (0.7 mile southeast of Milford, Milford quadrangle, New Hampshire): Medium to coarse biotite granite; coarse, granitic injection gneiss; fine-grained biotite granite; vitreous quartzite; and thinly foliated amphibolite are intimately associated in the southwest corner of the quarry. Although the sheet structure, which dips gently eastward, is much more regular in the granites than elsewhere, individual sheet fractures pass indiscriminately through all the rocks. Foliation of rocks: N. 60°–80° W., dip 40°–70° S.

6. Palm and Koleh quarry (1.5 miles north-northeast of Milford, Milford quadrangle, New Hampshire): Coarse pegmatitic gneiss is cut by a small plug of fine-grained biotite granite, with contact relations unusually well shown at the northeast corner and south end of the quarry. Sheet structure transects both rocks but is slightly less regular in the gneiss (see Fig. 5). Attitude of gneissic structure: N. 65°–70° E., dips vertical.

Not only is sheet structure generally conformable with the surface of hills, but it also is parallel to hollows and valleys. This synclinal or basin-like attitude was seen in several areas of nearly continuous exposures near Milford, New Hampshire, and on Oak Hill in Westford, Massachusetts, and has also been reported from the Sierras by Gilbert[9] and Matthes.[10]

Sheet structure, with its open fractures, has been observed at points as deeply within bodies of New England granites as artificial openings have been made. Thus it is known to extend to depths of at least 320 feet at Quincy, Massachusetts; 150 feet in the H. E. Fletcher quarry, Westford, Massachusetts; 200 feet at Barre, Vermont; and at least 150 feet on Crotch Island, Maine.

That many, if not most, New England granites are under considerable compressive strain is readily demonstrable. Individual, freshly exposed sheets on quarry floors have been known to split suddenly into two or more sheets, either by the scaling-off of broad, thin flakes or by the "popping-up" of new sheets several inches in thickness. Release of strain has been accomplished in many quarries on Oak Hill, Westford, Massachusetts, through development of vertical fissures and diagonal slip-fractures or through lateral expansion of sheets to fill artificial

[9] *Op. cit.* [10] *Op. cit.*, pp. 116–17.

openings. Thus, for example, several freshly cut channels in the Morris Brothers quarry have been suddenly narrowed to slightly more than half their original widths, and strike-slip movement of half an inch or more has occurred along others. Similar features have been reported from the H. E. Fletcher quarry, and many comparable examples from other quarries are listed by Dale.[11]

The characteristic features of sheet structure, as seen in the granites examined by the writer, may be summarized as follows:

1. Individual sheets are bounded above and below by flat to broadly undulatory fractures and characteristically are thin lenses or tabular masses. The thickest part of one sheet ordinarily lies in contact with relatively thin parts of the adjacent sheets.

2. The structure tends toward parallelism with the rock surface, both on hills and in depressions.

3. With increasing depth, the sheets generally become progressively thicker, flatter, and more regular.

4. Sheet structure is completely independent of all primary structures in the rock; and individual sheet fractures commonly transect small pegmatite, aplite, and granite dikes, as well as contacts with xenoliths, roof pendants, and the country rock itself.

5. Sheeting is best developed in the most sparsely jointed parts of a given rock mass.

6. Sheet fractures are present at and near the bottoms of the deepest New England granite quarries.

7. Definite evidence that many of the granites of New England are under compressive strain is observable in a large number of quarries, as well as in some natural exposures.

[11] *Op. cit.*, pp. 32–35.

ORIGIN OF SHEET STRUCTURE

Sheeting in granite was first described 145 years ago,[12] and since that time few rock structures have been attributed to such a variety of causes. Among the possible causes that have received most serious consideration are the following:

1. Tensional or contractional strains set up during cooling of an igneous mass, resulting in horizons of weakness oriented parallel to the walls of the mass or to some other primary surface.

2. Local or regional compressional stresses active after consolidation of the rock.

3. Insolation, with attendant daily and secular temperature changes.

4. Progressive hydration and formation of chemical alteration products in certain susceptible minerals.

5. Mechanical action of fire, frost, and vegetation.

6. Diminution of primary confining pressure (to which the rock has become adjusted) by removal of superincumbent load.

7. Combinations of the above causes.

Despite the glacial drift that mantles large areas, many of the granite bodies of northeastern Massachusetts, southern New Hampshire, and neighboring regions are well exposed. Furthermore, extensive quarrying operations have opened up numerous vertical sections, so that an unusually fine opportunity is afforded to evaluate the above-listed propositions in the light of abundant data. The possible causes of sheeting are discussed in the order given.

It is evident that sheet structure bears no genetic relation to the emplacement and consolidation of an igneous mass, for (*a*) its orientation is independent of all primary structures in the mass; (*b*) it

[12] See references in *ibid.*, p. 26.

transects contacts between the intrusive rock and xenoliths, roof pendants, and the country rock; (*c*) it transects later minor intrusive bodies within the mass; and (*d*) it is present with various orientations in injection gneisses, replacement granites, and similar rocks not of normal intrusive origin. Similarly, it is obvious that no direct relation exists between the attitude of sheeting in granite and the attitude of bedding in adjacent stratified rocks, even though in some places the two may appear to be parallel. This apparent parallelism probably moved Dale[13] to theorize that granite domes "may possibly be referred to major arches (anticlines) in the folds of the stratified rocks that originally overlay the granites." This suggestion hardly applies to the areas under consideration, where the rather gently dipping sheet structure in the granites is strongly contrasted with the very steeply dipping homoclinal bedding and foliation found throughout the surrounding metasediments. Further, steeply dipping injection gneisses of known sedimentary origin also show the characteristically gentle sheet structure. This is especially true in the Milford, New Hampshire, district.

The clear-cut relation of sheeting to topography, rather than to the shape of the granite body or to the structure of the surrounding country rock, naturally lends credence to the oft mentioned action of insolation as a fundamental cause. That it actually is a factor is further suggested by the marked effect of temperature on the ease and perfection of splitting in many granites. On the other hand, it should be borne in mind that (*a*) sheet structure extends to depths far beyond those to which insolation could possibly be effective; (*b*) granite in many areas is under severe compressive strain that is present to considerable depths, as shown, for example, by the sudden formation and spalling-off of new sheets on freshly exposed quarry floors; and (*c*) many well-sheeted exposures are situated on heavily wooded north slopes, where they receive little or no contact with the rays of the sun. Additional arguments, as well as field and experimental data that raise serious doubts concerning the efficacy of insolation as a producer of sheet structure, have been recorded by Eliot Blackwelder[14] and Rollin Farmin;[15] their views on this question are similar to those of Matthes[16] and Balk.[17]

It has been noted by some geologists[18] that considerable numbers of thin sheets commonly occur in New England granites at places where the glacial drift is thin or absent, whereas granite that is covered by several feet or more of drift may be much more thickly sheeted. This might be interpreted as strong evidence favoring the insolation hypothesis—at least for the development of the upper, thinner sheets—but it is equally true that very thinly sheeted granites also are covered by appreciable mantles of drift at many places, as, for example, at the H. E. Fletcher quarry, Westford, Massachusetts; the Henry Fletcher quarry, north of Littleton, Massachusetts; and the Palm and Koleh quarry, north of Milford, New Hampshire. Although the process of insolation cannot be disregarded entirely, its part in the production of sheet structure is evidently a minor one,

[13] *Ibid.*, p. 35.

[14] "Exfoliation as a Phase of Rock Weathering," *Jour. Geol.*, Vol. XXXIII (1925), pp. 793–806; "The Insolation Hypothesis of Rock Weathering," *Amer. Jour. Sci.*, Vol. XXVI (5th ser., 1933), pp. 97–113.

[15] "Hypogene Exfoliation in Rock Masses," *Jour. Geol.*, Vol. XLV (1937), pp. 625–35.

[16] *Op. cit.*, pp. 114–15. [17] *Op. cit.*, p. 310.

[18] G. F. Loughlin and L. W. Currier, oral communications, January, 1942.

and its effects must be confined to a relatively thin, surficial zone.

Development of rock stresses through mineral hydration and formation of chemical alteration products may well be an important contributory cause under favorable climatic conditions and at points near the rock surface, as suggested by Blackwelder.[19] In the granites of New England, however, the effects of this process must be slight, as demonstrated by the freshness of mineral grains along most sheet fractures. Even microscopic examination of specimens taken from near-surface sheets reveals no signs of severe weathering. It should be borne in mind, moreover, that sheet structure is a feature distinctly different in origin and significance from the "exfoliation" of spheroidally weathered rock masses.

The exfoliation of stone blocks in burned buildings, of boulders in burned-over woodland areas, and of the rock along the roofs of unlined railway tunnels bears testimony to the production of powerful stresses by strongly directed heat. Similarly, the mechanical action of frost and the roots of trees is capable of fracturing exposed rock. These processes can be effective, however, only near the surface and under peculiarly favorable conditions; hence they cannot be regarded as more than minor, subsidiary causes of sheet structure.

The most probable fundamental cause appears to be dilation upon the relief of a primary confining pressure—to which the rock has become adjusted—through removal of superincumbent load. This has been suggested by several geologists, among them Gilbert,[20] Matthes,[21] G. W. Bain,[22] Farmin,[23] and Balk.[24] The process has been clearly described by Farmin,[25] who states:

> The unloading of rock masses is continually in progress as erosion brings nearer and nearer to the surface rocks adjusted to the heavy pressure which must prevail in the deeper portions of the earth's crust. The unloaded rock will tend to expand and will do so by fracture wherever internal stress exceeds its elastic strength.

He continues, in speaking of a plutonic or a deeply buried or folded sedimentary or volcanic rock, as follows:

> When erosion brings a rock of this type to the surface a dilation of the rock will tend to ensue, proportionate to the unloading. The dilation may cause doming and exfoliation, independent of weathering. As the rock is weakened by the subsequent attack of weathering, a further exfoliation may develop at points where the rock was strong enough to withstand its internal stress before attack.

With gradual unloading of a granitic rock the released forces within it should be directed toward the nearest exposed surface. This is in agreement with the observed general parallelism between topography and the concentric shells, or sheets, formed by expansion of the rock. Release of these forces should chiefly occur through movements among pre-existing fracture planes in jointed rocks rather than by development of many new fractures; this also is in accord with existing conditions, since the least jointed granites are the most thinly and regularly sheeted. The evidence of compressive strain in quarries and natural exposures, the youthfulness of sheet structure with respect to primary structures in the granite and with respect to structure of the adjacent country rock, the depths to which sheeting is known to extend, and

[19] "Exfoliation as a Phase. . . . ," *op. cit.*; "The Insolation Hypothesis . . . . ," *op. cit.*

[20] *Op. cit.*, pp. 29–36.

[21] *Op. cit.*, p. 115; "Exfoliation of Massive Granite in the Sierra Nevada of California" (abstr.), *Proc. Geol. Soc. Amer. 1936* (1937), pp. 342–43.

[22] "Spontaneous Rock Expansion," *Jour. Geol.*, Vol. XXXIX (1931), pp. 715–35.

[23] *Op. cit.*

[24] *Op. cit.*, pp. 310–11.

[25] *Op. cit.*, pp. 632–33.

the gradual downward changes in attitude and thickness of the sheets themselves are characteristic features entirely compatible with an origin involving dilatancy through removal of overlying load. Moreover, laboratory experiments by several independent investigators[26] have demonstrated that cylinders and spheres of limestone and other naturally occurring substances, if suitably compressed, commonly develop typical exfoliation shells upon relief of the pressure.

GLACIAL EROSION ON GRANITE HILLS

GENERAL STATEMENT

Erosion beneath the ice sheets that covered New England during the Pleistocene must have been a highly irregular process. That it did occur to a significant degree at many individual localities can be proved easily enough, as shown, for example, by N. S. Shaler,[27] B. K. Emerson,[28] W. H. Hobbs,[29] and W. J. Miller,[30] and yet its actual magnitude at these localities has remained in doubt. The more general amounts of erosion accomplished by continental glaciers have been discussed and variously estimated by many geologists, few of whom have reached complete agreement. Although the arguments and enumerated points of evidence are stimulating, their treatment is beyond the scope of this paper; the reader is instead referred to an excellent summary discussion by F. T. Thwaites,[31] who concludes that "erosion by continental glaciers was undoubtedly of major importance only where favored by rough topography, mechanically weak rocks, and concentrated flow."

Without question the topography of northwestern Massachusetts and adjacent parts of southern New Hampshire must have been peculiarly favorable to glacial erosion, especially by plucking or quarrying. With a total relief that exceeds 500 feet in few places, much of the area is nevertheless hilly and has many steep slopes. Moreover, the hilly areas generally are separated by fairly broad valleys; these must have minimized the importance of a process cited by Thwaites,[32] in which considerable parts of the bases of continental ice sheets "are caught between hills and left stagnant, the upper ice shearing over these parts." The low over-all relief of the region would also militate against such occurrences. Finally, many rock hills exposed at isolated positions within rather extensive lowland areas must have been particularly susceptible to glacial plucking and abrasion.

GLACIAL EROSION AND SHEET STRUCTURE

Sheet structure in granites was shown to be preglacial in origin as early as 1879.[33] That the formation of sheet or exfoliation fractures, even to depths of a few tens of feet, requires thousands of centuries has been clearly shown by

[26] See, e.g., F. D. Adams, "An Experimental Investigation into the Action of Differential Pressure on Certain Minerals and Rocks," *Jour. Geol.*, Vol. XVIII (1910), p. 517; P. W. Bridgman, "Reflections on Rupture," *Jour. Appl. Phys.*, Vol. IX (1938), pp. 517–28.

[27] "The Conditions of Erosion beneath Deep Glaciers, Based upon a Study of the Boulder Train from Iron Hill, Cumberland, Rhode Island," *Bull. Harvard Mus. Comp. Zoöl.*, Vol. XVII (1893), pp. 192–96, 207–14.

[28] "Geology of Old Hampshire County, Massachusetts," *U.S. Geol. Surv. Mono. 29* (1898), pp. 518–21.

[29] "An Instance of the Action of the Ice upon Slender Projecting Rock Masses," *Amer. Jour. Sci.*, Vol. XIV (4th ser., 1902), pp. 399–403.

[30] "Ice Movement and Erosion along the Southwestern Adirondacks," *Amer. Jour. Sci.*, Vol. XXVII (4th ser., 1909), pp. 289–98.

[31] *Outline of Glacial Geology* (Ann Arbor, Mich.: Edwards Bros., Inc., 1934), pp. 19–21.

[32] *Op. cit.*, p. 19.

[33] Vogt, *op. cit.*

Matthes,[34] who enumerates several localities in the Yosemite region at which granite masses that "were stripped of all their shells by the overriding Merced Glacier of the Wisconsin stage, still show no signs of renewed exfoliation over the greater part of their surfaces." In many places, therefore, the postglacial interval of about two hundred centuries has been too short for the opening of a single new sheet (or exfoliation) fracture. Similarly, only a few shells (or sheets) have formed parallel to surfaces exposed since the El Portal glaciation, or for a period estimated by Matthes[35] to be about two thousand centuries. Naturally, these data must be extrapolated to rock masses in other areas with considerable caution; nevertheless, it is certain that very few sheet fractures have formed since Wisconsin time in those areas where data are available.

The great granite domes of unglaciated regions, such as Stone Mountain, Georgia, and Mount Airy, North Carolina, owe their smooth, sweeping curves to the long-continued action of progressive exfoliation. It seems reasonable to assume that the granite hills of New England, having experienced hundreds of centuries of denudation, were somewhat similar features at the close of Tertiary time and that the configuration of their surfaces was broadly controlled by sheet planes. During the glacial epoch these sheeted granites, which are divided into angular blocks by steeply dipping joints and shear planes (see Fig. 2), must have been easily plucked and quarried by the advancing ice. The large number of angular granite blocks in the drift bears testimony to this process, the mechanism and effects of which have been described in detail by Matthes.[36]

[34] "Geologic History . . . . ," *op. cit.*, pp. 115–16.
[35] *Ibid.*, p. 115.
[36] *Ibid.*, pp. 89–102.

After removing all patches of regolith, glacial ice would normally abrade and thus smooth the resistant granite on the stoss side of a given hill. On the other hand, it would excavate and carry away considerable quantities of fractured rock from the lee side, almost wholly by plucking and quarrying. Somewhat smaller amounts of granite presumably would be removed from the top and other sides of the hill by combinations of the above processes. Thus we should expect most granite hills in New England to have relatively smooth and regular north and northwest slopes that are rather strictly conformable with underlying sheet structure; somewhat less regular east and west slopes on which the exposed edges of a few sheets are visible; and abrupt, irregular south and southeast slopes, on which the torn edges of many sheets are exposed or are buried by drift.

Ideal sections of a hypothetical granite hill are shown in Figure 7. The upper section illustrates the hill profile as it may well have appeared before glaciation, with topography in general controlled by sheet structure. The lower section shows the hill at the present time, with maximum glacial erosion having occurred on its south slope. Appreciable amounts of rock have been removed from its top, in large measure because supporting rock had been excavated from the upper part of the lee slope. The most feeble erosive action on such a hill was on the north, or stoss, slope. That the lower of these ideal sections is strikingly similar to many existing granite hills in northeastern Massachusetts and southern New Hampshire will be shown in the following section of this paper.

It is evident that reconstruction of the preglacial profile of a hill (Fig. 7, *a*) by means of present-day attitudes of sheet structure is impossible, chiefly because

the absolute altitude of the preglacial surface cannot be determined. It is possible, however, to construct a profile (Fig. 7, *b*) that lies approximately parallel to the preglacial profile and beneath it by an amount equal to the depth of across individual pre-existing sheets that do not conform to the present surface, but in most places even the thinnest upper sheets can be shown to pass unchanged beneath appreciable thicknesses of glacial drift. The edges of the much

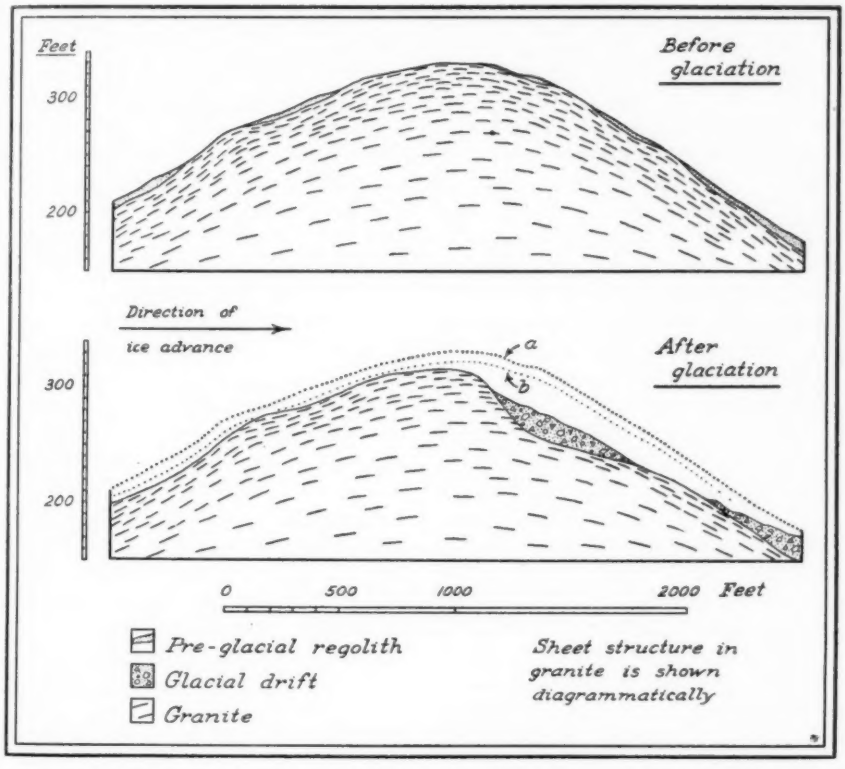

FIG. 7.—Idealized cross sections of a granite hill, showing relations between topography and sheet structure before and after glaciation.

erosion on the least affected part of the hill (usually the north slope). Thus a minimum quantitative estimate of glacial erosion can be obtained for certain specific localities.

The formation of newly oriented sheets parallel to postglacial surfaces has been almost negligible. Here and there a single exfoliation plane has developed heavier, severely plucked sheets on the lee sides of hills are commonly covered by thick glacial deposits. The postglacial formation of thin sheets parallel, rather than transverse, to pre-existing sheeting is a process whose existence cannot be denied, because new sheets have been known to form even on the freshly exposed floors of some quarries. Such post-

glacial sheets, however, are necessarily confined to near-surface portions of the rock and are relatively insignificant.

An interesting phenomenon described by Dale[37] as double-sheet structure is perhaps explainable in the light of glacial erosion. This structure characteristically involves a set of thick, regular, and gently dipping sheets, some of which are transected by a clearly younger set of thinner, more irregular ones that lie more nearly parallel to the hill slope. The younger sheet fractures appear to be selectively developed in each of several very thick sheets of the earlier, more nearly horizontal set. It seems significant that wherever this structure has been noted, the hill slope is so situated that it should have experienced unusually severe erosion by any southward or southeastward advancing ice sheet. The older and more regular sheets thus might be considered preglacial, whereas the younger ones have been developed parallel to a surface formed through unusually heavy erosion by a pre-Wisconsin ice sheet. This suggested interpretation is in agreement with the statements of Matthes[38] concerning the reorientation of exfoliation following glacial remodeling in the Yosemite region; and it supports the thesis that sheeting broadly controls topography when denudation is relatively slow and long continued but is reoriented when strongly concentrated erosion by water or ice creates relatively rapid topographic changes.

EXAMPLES IN THE CHELMSFORD GRANITE BELT, MASSACHUSETTS

The Chelmsford granite.—The Chelmsford granite,[39] which was originally considered a part of the Ayer granite by Emerson,[40] is exposed in a long, narrow belt that extends eastward and northeastward from the vicinity of Ayer, Massachusetts (see Fig. 1). Small additional bodies appear in areas north of Ayer and north of Dunstable. The rock is a uniformly foliated, fine- or medium-grained, very light gray muscovite-biotite granite and is one of the most distinctive units in the entire region. It contains many thin, straight, closely spaced, and remarkably uniform biotite-rich layers, whose attitude generally is distinctly discordant from that of the foliation, or alignment, of individual mica flakes. Where the layers are sufficiently thick, the rock tends to split along them (Fig. 4).

Much of the area underlain by the Chelmsford granite is rough and hilly; the large number of quarries and natural exposures on some of these hills permits close study of the rock structure. In general the granite is traversed by rather regular joint sets, individual joints in which are ordinarily at least 15 feet apart. Shear zones are also present but are much more common in the valley areas. Thin, irregularly distributed dikes of muscovite-rich aplite and pegmatite establish additional surfaces of weakness in the rock.

Fletcher Hill and vicinity.—Two small hills characteristic of the western part of the Chelmsford granite belt (Fig. 1, *A*) are shown in Figure 8 (see also Ayer quadrangle). Both are ovoid in plan and rise to heights of 200 feet or less above the surrounding lowlands, which are cov-

[37] *Op. cit.*, p. 36.

[38] "Geological History . . . . ," *op. cit.*, p. 115; "Exfoliation of Massive Granite . . . . ," *op. cit.*

[39] L. W. Currier, "The Problem of the Chelmsford, Massachusetts, Granite" (abstr.), *Trans. Amer. Geophys. Union 18th Ann. Meeting* (1937), pp. 260–61.

[40] "Geology of Massachusetts and Rhode Island," *U.S. Geol. Surv. Bull. 597* (1917), pp. 223–26.

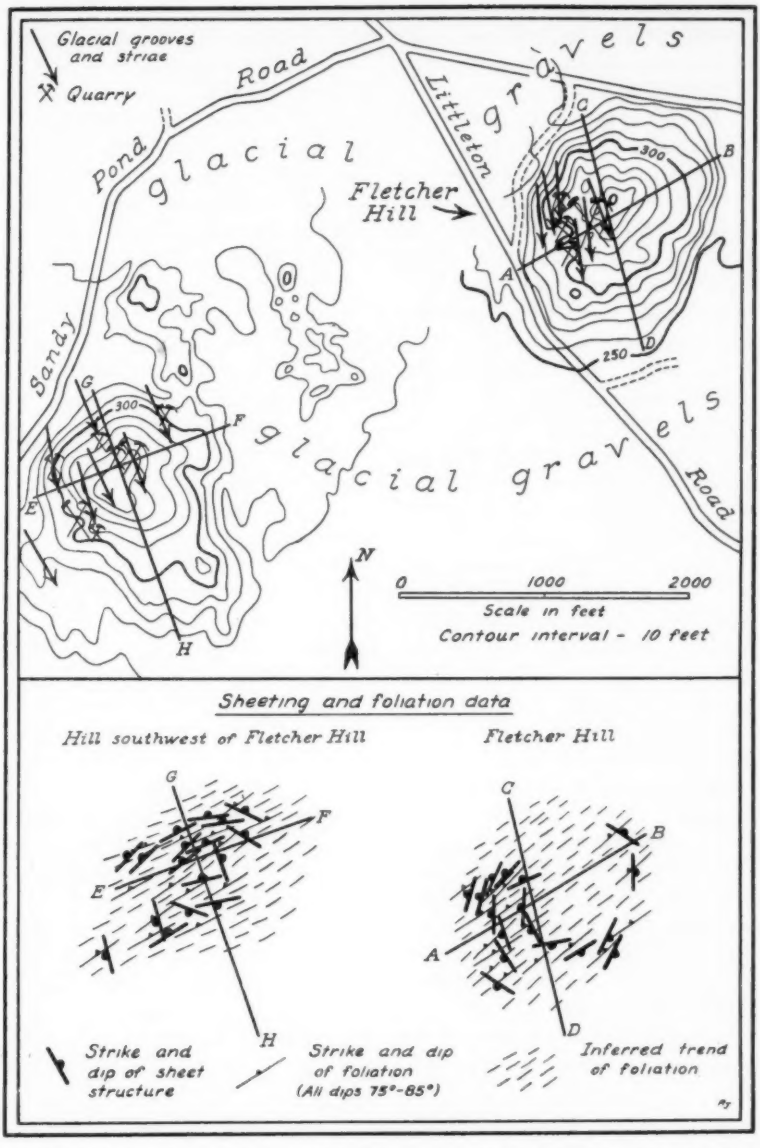

FIG. 8.—Sketch maps of Fletcher Hill and vicinity, showing relations between topography, sheet structure, and foliation in Chelmsford granite. Topography from Ayer quadrangle, U.S. Geological Survey.

ered with glacial outwash gravels. The slopes on the north, east, and west sides of each hill are rather smoothly contoured; on their south sides, however, the bedrock surfaces are very rough and irregular, as well as distinctly steeper.

Both foliation and layering in the granite strike northeast and dip steeply northwest, as indicated in the lower part of Figure 8. The sheet structure, on the other hand, dips gently and quaquaversally on each hill. That the sheets do not everywhere lie parallel to the hill slopes is evident from an inspection of representative cross sections (Fig. 9). The dotted lines in these sections represent profiles thought to be parallel to and at some distance below the profiles of the preglacial surfaces; they were constructed parallel to the existing sheet structure on the basis of assumptions previously discussed.

Section *AB* (Fig. 9), transverse to the direction of ice movement, suggests that a rather uniform cover of rock at least 10 feet thick was removed from the upper parts of Fletcher Hill, presumably by plucking and abrasion. A section parallel to the direction of ice movement (Fig. 9, *CD*) presents a totally different picture. Removal of at least 40 feet of granite from the south slope of the hill is suggested, whereas relatively little erosion seems to have been accomplished on the north slope. These estimates of depth of removal obviously represent minimum figures; the depth actually may well have been much greater, depending upon the amount of over-all erosion on the hill (see Fig. 7).

The small hill southwest of Fletcher Hill presents similar relations. Section *EF* (Fig. 9), athwart the direction of ice advance, shows moderate amounts of erosion on the top and west-southwest side and the stripping-off of sheets to depths of 25 feet or more on that part of the hill east-northeast of its summit. The section parallel to the trend of ice movement (*GH*) suggests excavation of at least 30 feet of granite from the south-southeast side (dotted line *a*); if the erosion at the summit, as shown in section *EF*, is taken into consideration, the plucked-off rock layers in *GH* must have been at least 40 feet thick (dotted line *b*).

Oak Hill.—Oak Hill, which lies about two miles west of North Chelmsford (see Fig. 1, *B*, and Tyngsboro quadrangle), is a broad-topped, steep-sided granite mass that is bounded immediately to the northwest (near Flints Corner, Fig. 10) by a terrane of quartzite and biotite schist. More than forty quarries have been opened on this hill and on the more subdued hills immediately to the east and southeast; hence the Chelmsford granite there is unusually well exposed. As shown in Figure 10, the pattern of its foliation is very regular, with only gentle changes in trend; mineralogic layering in the granite trends nearly parallel with the foliation but ordinarily dips less steeply.

Superimposed on these primary structures is a well-developed sheet structure that tends to conform to the contour of the hill slopes in most places (see Fig. 10). This is especially true on the north, east, and west slopes of Oak Hill. A mile southeast, the H. E. Fletcher quarry, now one of the largest in the United States, was first opened on the summit of a small, very low hill; at present the sheeting can be seen to dip very gently and quaquaversally with respect to the center of the quarry (Fig. 15), which now occupies the original position of the entire hill.

The western spur of Oak Hill, on which the large Morris Brothers quarry

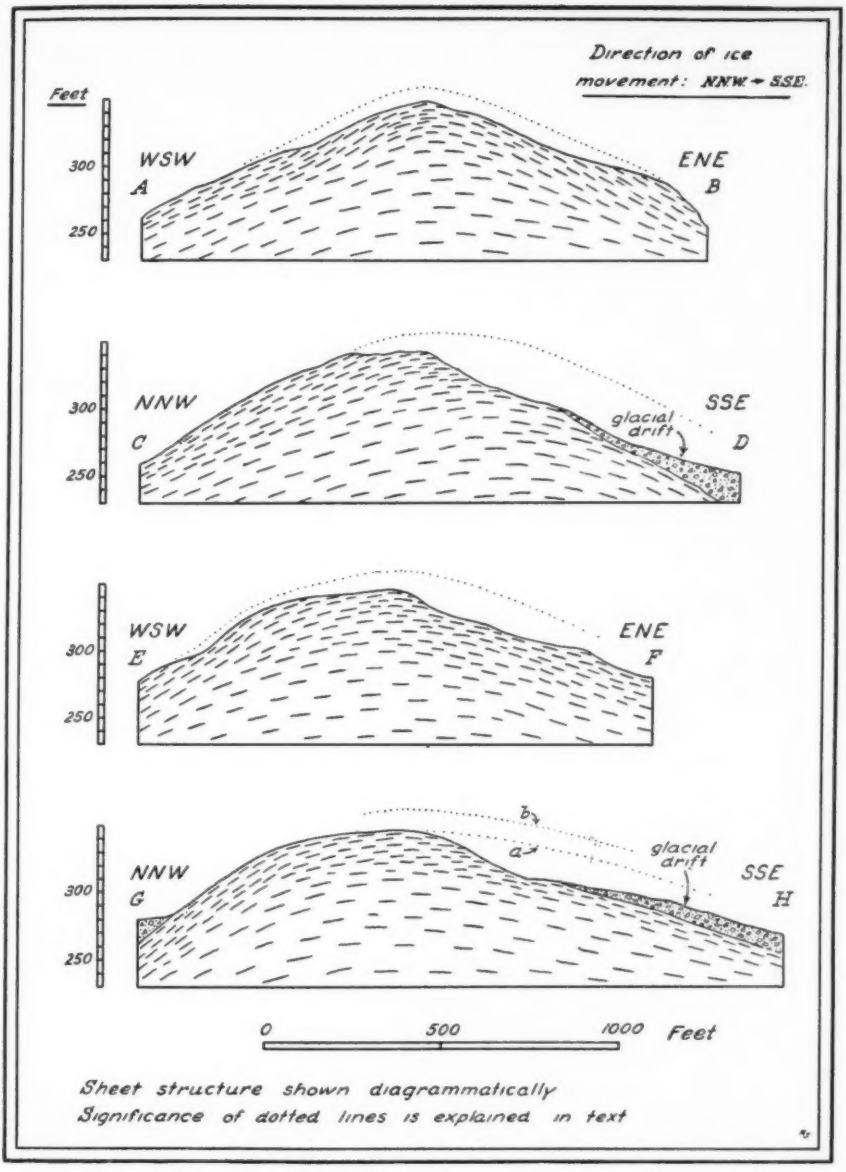

FIG. 9.—Representative cross sections of Fletcher Hill and the hill to the southwest, showing relations between sheet structure and topography.

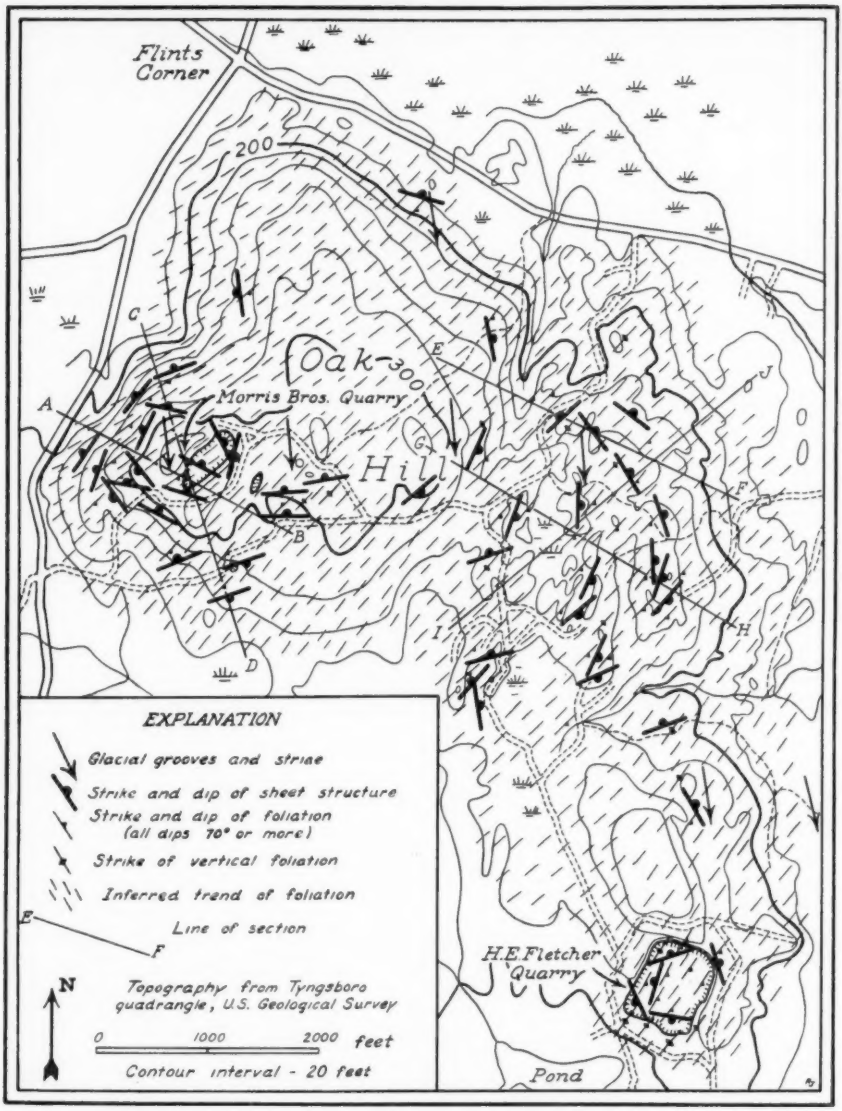

FIG. 10.—Sketch map of Oak Hill and vicinity, showing relations between topography, sheet structure, and foliation in Chelmsford granite.

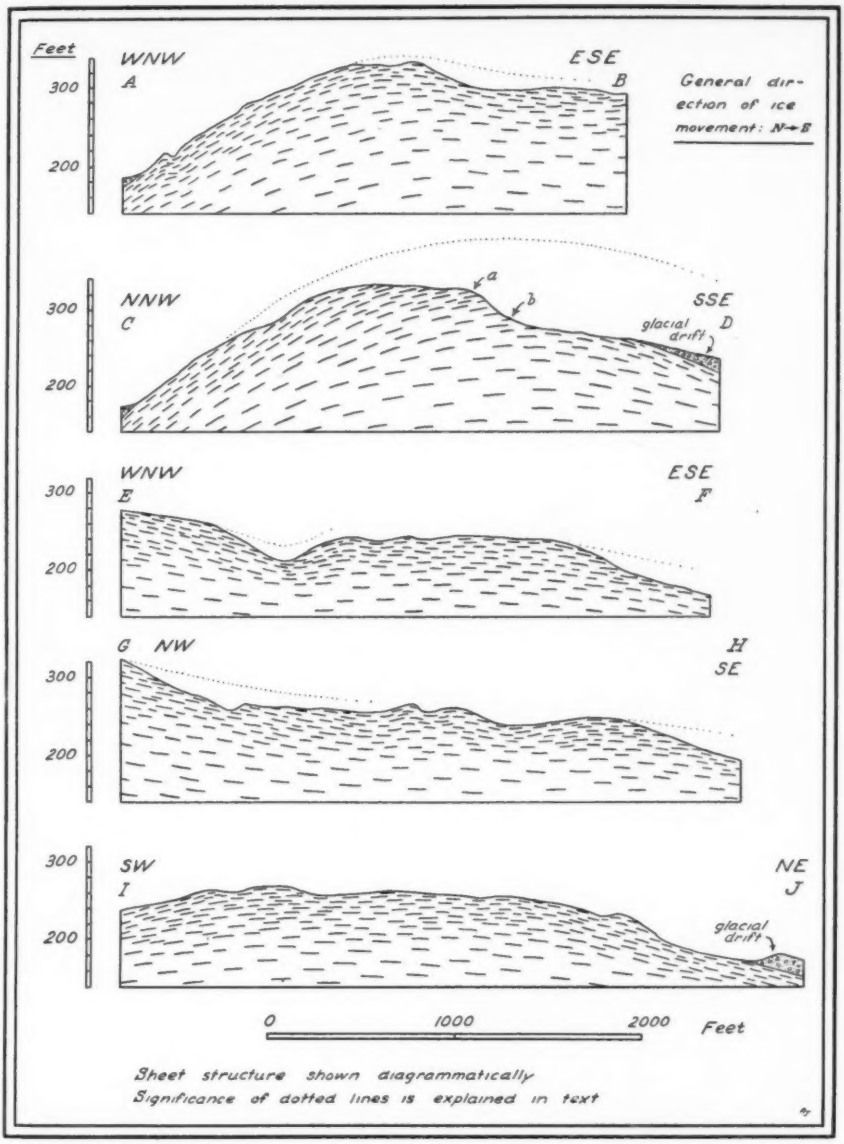

FIG. 11.—Representative cross sections of Oak Hill and adjacent hills, showing relations between sheet structure and topography.

is located, has experienced more glacial remodeling than any other hill examined by the writer. So great has been the plucking and quarrying of rock from the upper parts of its south slope that the sheet structure there actually dips to the north (*a* to *b*, section *CD*, Fig. 11). Figure 12, a view looking south in the Morris Brothers quarry, shows this northward dip. The derrick stands near the summit of the hill, and the building in the right distance marks the upper edge of its steep, irregular south slope. Recent quarrying operations beyond and to the right of the building (at the intersection of road and section *CD* in Fig. 10) have exposed thick sheets that dip 7°–13° north.

FIG. 12.—Sheet structure in Chelmsford granite, looking south in Morris Brothers quarry, Oak Hill, Westford, Massachusetts (see also Figs. 10 and 11). Slope of hill drops off rapidly beyond shed in right background, although sheet structure dips gently toward the observer.

As shown in section *CD* (Fig. 11), which trends approximately parallel to the direction of ice movement, at least 110 feet of rock appears to have been excavated from the south and southeast sides of the hill, and a somewhat lesser amount from the top. This large-scale removal of material has exposed several 8–11-foot sheets in the vicinity of the Morris Brothers quarry (point *a*); in quarries to the southeast (point *b*), where erosion was even greater, correspondingly thicker sheets are present at and near the surface. Section *AB* (Fig. 11) trends obliquely with respect to the direction of ice advance (see Fig. 10) and thus includes a part of the hill from which a relatively small amount of granite was removed by lee-side plucking. The west-northwest side of the hill, on the other hand, experienced almost no differential glacial erosion, and the sheet structure there lies in close accord with the steep but rather smooth slope.

Section *EF* (Fig. 11) illustrates several interesting relations in the area east of Oak Hill. A narrow, steep-walled valley about 30–80 feet deep is underlain by granite whose sheet structure is concave upward. Despite the changes wrought in

this small valley by Quaternary erosion, its original control of underlying sheet structure and, therefore, its existence as a preglacial depression are evident. The dotted line denotes its lowest possible preglacial profile. The part of the hill shown on the right-hand side of the section was a lee slope with respect to the advancing glacial ice and thus experienced a strong plucking action that appears to have extended to a depth of at least 30 feet.

Sections *GH* and *IJ* show typical relations on the more subdued hills southeast and east of Oak Hill itself. Selective plucking and quarrying of rock evidently lowered the surface several tens of feet in favorable places, but in general the amount of differential glacial erosion seems to have been relatively small.

Snake Meadow Hill.—Snake Meadow Hill is a large, ovoid rock mass that rises more than 200 feet above its surrounding area in Westford, Massachusetts (Fig. 1, *C;* see also Westford quadrangle). It is underlain by Chelmsford granite everywhere but on its lower northwest slopes. As in other areas, the foliation in the granite trends northeast and dips very steeply. The attitudes of mineralogic layering are comparable.

Natural exposures on the rather smooth and uniformly sloping north, east, and west sides demonstrate the close accord there between topography and sheeting. Quarries on the east side show this even more clearly. The south slope of the hill, however, is rough, hackly, and much steeper; quarries there exhibit the exposed edges of sheets that dip more gently than the present bedrock surface. These relations are analogous to those at the representative localities already discussed and suggest that at least 50 feet—possibly much more—of granite was removed by glacial plucking and quarrying from the upper parts of the south side.

Of additional interest are two narrow ravines on the southwest slope of the hill. They lie immediately west of the south-side quarries and are about 1,200 feet long and 20–45 feet deep. That two small valleys existed in essentially these areal positions in pre-Wisconsin (and probably preglacial) time is suggested by the upward concavity of the sheet structure beneath them. As in the small canyon already described from the northeast side of Oak Hill, the walls of these ravines have been modified somewhat by glacial erosion as well as by interglacial and postglacial stream action, but the attitude of the sheeting nevertheless reflects their presence.

OTHER EXAMPLES

Kittredge Hill.—Kittredge Hill is located about 1½ miles south-southwest of Milford, New Hampshire (see Fig. 1, *D*, and Milford quadrangle); on it are several large granite quarries that have been described by Dale.[41] As shown in Figure 13, the hill has the general form of an elongated dome that rises nearly 150 feet above the surrounding lowlands. It is underlain chiefly by a coarse, granitic injection gneiss and a fine- to medium-grained biotite granite. The granite is intrusive into the gneiss and appears in outcrop as a ringlike belt around the hill (Fig. 13). All observed contacts dip moderately to steeply toward the center of the hill; biotite-rich flow-schlieren and other structures of like origin also dip into the hill (see attitudes in Fig. 13). The central gneiss mass thus may well be a downward-tapering xenolith or roof pendant. Both granite and gneiss are cut by dikes of fine-grained granite (Fig. 6).

All rock types are cut indiscriminately

[41] *Op. cit.*, pp. 183–85.

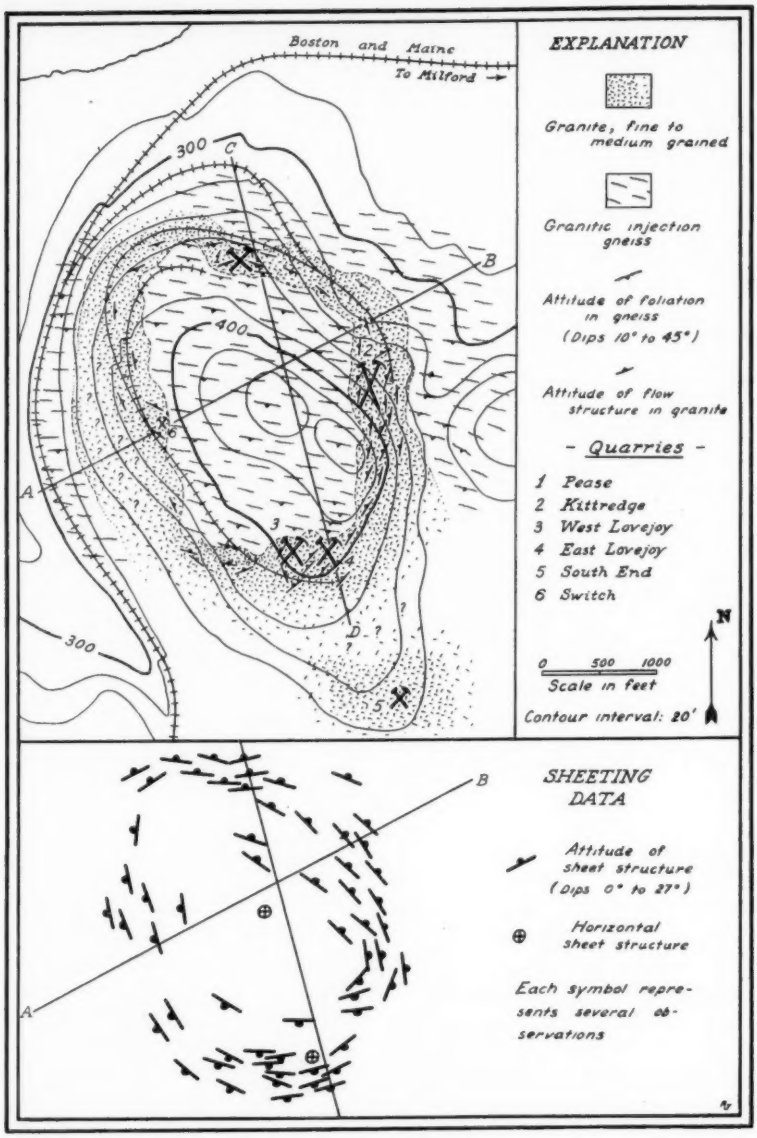

FIG. 13.—Geologic sketch map of Kittredge Hill, showing distribution of rock types and of primary structures therein. Data for sheet structure shown below.

by sheet structure which slopes gently and quaquaversally from the summit of the hill (see sheeting data, Fig. 13). The general relations between sheeting and topography are shown in the two representative sections in Figure 14, one athwart the direction of ice movement (*AB*) and one parallel to it (*CD*). Both sections suggest that at least 25–40 feet of rock has been abraded and plucked from the summit and gentle upper slopes of the hill. The severe lee-side plucking so common elsewhere does not appear to have been operative on Kittredge Hill, probably because of the very gradual slope of its south-southwest side. A smooth-contoured rock ridge actually extends from the lee side in the vicinity of the Lovejoy quarries (Fig. 13) to a point well beyond the South End quarry.

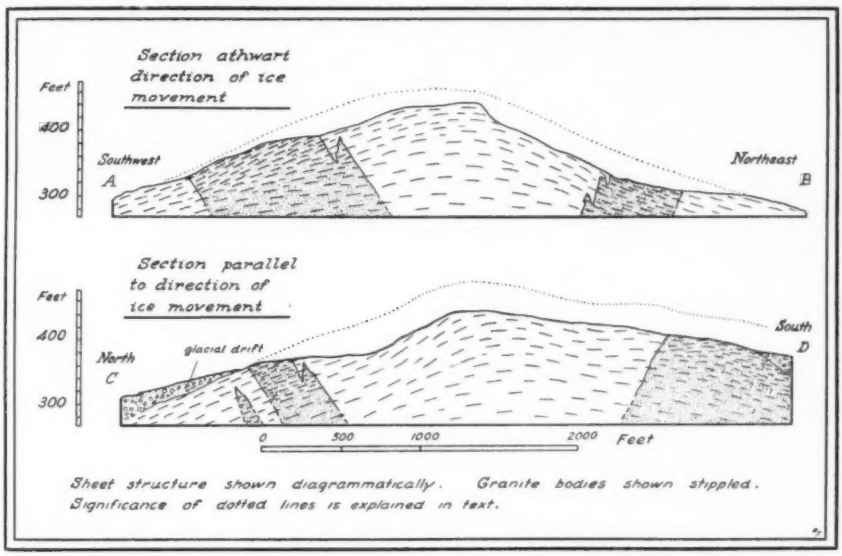

FIG. 14.—Cross sections of Kittredge Hill, showing relations of rock types, sheet structure, and topography.

Rollstone Hill.—Rollstone Hill is a prominent rock mass that lies about a mile west of the railroad station in Fitchburg, Massachusetts (see Fitchburg quadrangle and Fig. 1, *E*), and rises with steep but uniform slope for more than 300 feet above the south edge of the narrow valley of the Nashua River. It is elliptical in plan, with its long axis trending north-northwest, or parallel to the general direction of Pleistocene glaciation. Underlying the entire hill is the Fitchburg granite,[42] a medium-grained, gneissic muscovite-biotite granite, the foliation of which strikes slightly east of north and dips moderately to steeply west.

Sheet structure is well developed, lies horizontal at the top of the hill, and dips away from the summit on all sides. That it is in close accord with the present rock surface on the smooth, bare north slope can be readily seen from the streets of the city below. Quarries on the north-

[42] Emerson, "Geology of Massachusetts . . . .," *op. cit.*, pp. 231–33.

east, west, and southwest sides of the hill show the same relations. The south and southeast sides, however, are somewhat steeper and more irregular, and the exposed edges of granite sheets thereon suggest the removal of considerable amounts of rock by glacial plucking. Insufficient exposures make it impossible to estimate the amount of general glacial erosion, but at least a few tens of feet of granite appear to have been selectively plucked from parts of the southeast side of the hill.

SUMMARY AND CONCLUSIONS

With very few exceptions the sheet structure on the granite hills of New England appears to be preglacial in origin. Sheet structure in general is known to be formed approximately parallel to the exposed rock surface; hence, some idea of the preglacial configuration of such hills in northeastern Massachusetts and southern New Hampshire can be obtained by a study of the present attitude of the sheets as related to present topography. The absolute amount of material removed by glacial erosion cannot be estimated by this method, but the approximate differential between the least and the most severely eroded parts of a given hill can be obtained if sufficient exposures are available.

As the result of detailed observations on more than twenty granite hills, the following conclusions seem to be justified:

1. A blanket of rock and preglacial regolith at least 10–15 feet thick has been removed by glacial plucking and abrasion from the stoss, or north, slopes of most hills, and a somewhat greater amount from their east slopes, summits, and west slopes.

2. This glacial erosion was most severe on isolated hills that occupy positions well within lowland areas and on hills so situated that they were exposed to strongly directed and concentrated ice flow.

3. The greatest amounts of material have been thus removed from areas underlain by intricately jointed granite.

4. The excavation of great thicknesses of rock by glacial plucking and quarrying has profoundly altered the configuration of the lee, or south and southeast slopes of many hills, especially those with rather steep preglacial slopes underlain by massively jointed granite. The maximum demonstrable depth of such localized erosion is in excess of 100 feet.

GRANITE BOULDERS AND GLACIAL EROSION

GENERAL STATEMENT

It has been demonstrated that the thickness of granite sheets increases gradually with depth. Observations in many quarries suggest that there is a certain amount of quantitative consistency in the relation between sheet thickness and depth within a given granite body. It seems possible, therefore, that the sizes of large granite boulders—and consequently the thicknesses of the sheets from which they were derived—may furnish an additional clue to the depth of glacial erosion in their source areas.

THICKNESS AND DEPTH OF GRANITE SHEETS

Although the exfoliation sheets or shells in a granite body thicken gradually with depth, they tend to do so in a manner highly irregular in detail (see Figs. 3, 6, 15). Five- and six-foot sheets may appear abruptly within a section of much thinner ones, and, conversely, relatively thin sheets commonly occur between much thicker ones in the deeper parts of large quarries (Fig. 15). The more heavily jointed parts of a rock mass tend to

be more massively sheeted or may even appear to lack sheeting entirely, as in certain quarries in the Barre, Vermont, district. On the other hand, adjacent, less fractured parts of the mass may be divided into a large number of sheets. Thickness and degree of perfection of sheet structure also vary with textural and mineralogic changes in the granite and certainly might be expected to vary within granites with different geologic histories.

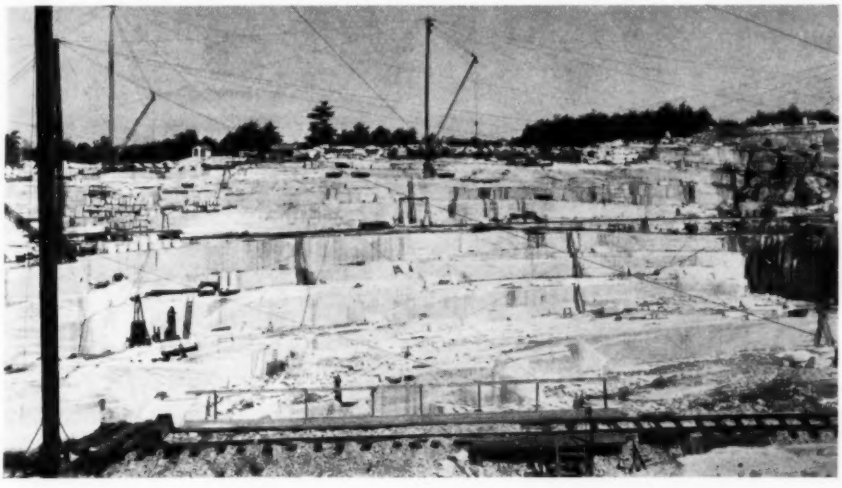

FIG. 15.—H. E. Fletcher quarry, Westford, Massachusetts. Note increasing regularity, thickness, and flatness of sheets with depth. Bottom sheet seen on right in the photograph is 18 feet thick.

It is evident that observations on the relations between thickness and depth of sheets, if they are to be of any real value, must be made in a single granite body that is rather uniform in composition, texture, and structure. If it is jointed, the joints should have a reasonably uniform distribution. The Chelmsford granite, as exposed within the areas under consideration, meets all these requirements. Moreover, its main belt (Fig. 1), which lies athwart the direction of glacial ice movement, is bounded on the northwest by wholly different rock types, so that the approximate sources of large glacial boulders of this granite are seldom in doubt.

In view of the desired correlation between size of boulders and minimum depth of glacial erosion, we must determine the *minimum* rather than the *average* depth at which a sheet of specified thickness is encountered in the granite mass. This depth, unfortunately, cannot be referred to the preglacial surface, because no quarry in the region has been opened downward from such a surface. The southeast face of the H. E. Fletcher quarry in Westford, Massachusetts, however, does appear to be a section through a part of the granite body that has been less severely eroded than most. The sheets contained therein are listed in Table 1. Doubtless, additional thin sheets were present in preglacial time, but this is thought to be the nearest approach to a complete section obtainable in the district. The thicknesses of its

east, west, and southwest sides of the hill show the same relations. The south and southeast sides, however, are somewhat steeper and more irregular, and the exposed edges of granite sheets thereon suggest the removal of considerable amounts of rock by glacial plucking. Insufficient exposures make it impossible to estimate the amount of general glacial erosion, but at least a few tens of feet of granite appear to have been selectively plucked from parts of the southeast side of the hill.

SUMMARY AND CONCLUSIONS

With very few exceptions the sheet structure on the granite hills of New England appears to be preglacial in origin. Sheet structure in general is known to be formed approximately parallel to the exposed rock surface; hence, some idea of the preglacial configuration of such hills in northeastern Massachusetts and southern New Hampshire can be obtained by a study of the present attitude of the sheets as related to present topography. The absolute amount of material removed by glacial erosion cannot be estimated by this method, but the approximate differential between the least and the most severely eroded parts of a given hill can be obtained if sufficient exposures are available.

As the result of detailed observations on more than twenty granite hills, the following conclusions seem to be justified:

1. A blanket of rock and preglacial regolith at least 10–15 feet thick has been removed by glacial plucking and abrasion from the stoss, or north, slopes of most hills, and a somewhat greater amount from their east slopes, summits, and west slopes.

2. This glacial erosion was most severe on isolated hills that occupy positions well within lowland areas and on hills so situated that they were exposed to strongly directed and concentrated ice flow.

3. The greatest amounts of material have been thus removed from areas underlain by intricately jointed granite.

4. The excavation of great thicknesses of rock by glacial plucking and quarrying has profoundly altered the configuration of the lee, or south and southeast slopes of many hills, especially those with rather steep preglacial slopes underlain by massively jointed granite. The maximum demonstrable depth of such localized erosion is in excess of 100 feet.

GRANITE BOULDERS AND GLACIAL EROSION

GENERAL STATEMENT

It has been demonstrated that the thickness of granite sheets increases gradually with depth. Observations in many quarries suggest that there is a certain amount of quantitative consistency in the relation between sheet thickness and depth within a given granite body. It seems possible, therefore, that the sizes of large granite boulders—and consequently the thicknesses of the sheets from which they were derived—may furnish an additional clue to the depth of glacial erosion in their source areas.

THICKNESS AND DEPTH OF GRANITE SHEETS

Although the exfoliation sheets or shells in a granite body thicken gradually with depth, they tend to do so in a manner highly irregular in detail (see Figs. 3, 6, 15). Five- and six-foot sheets may appear abruptly within a section of much thinner ones, and, conversely, relatively thin sheets commonly occur between much thicker ones in the deeper parts of large quarries (Fig. 15). The more heavily jointed parts of a rock mass tend to

be more massively sheeted or may even appear to lack sheeting entirely, as in certain quarries in the Barre, Vermont, district. On the other hand, adjacent, less fractured parts of the mass may be divided into a large number of sheets. Thickness and degree of perfection of sheet structure also vary with textural and mineralogic changes in the granite and certainly might be expected to vary within granites with different geologic histories.

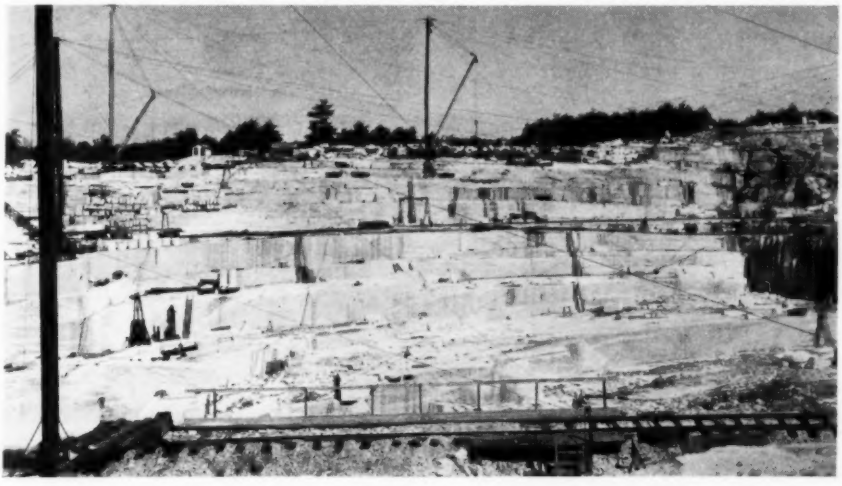

FIG. 15.—H. E. Fletcher quarry, Westford, Massachusetts. Note increasing regularity, thickness, and flatness of sheets with depth. Bottom sheet seen on right in the photograph is 18 feet thick.

It is evident that observations on the relations between thickness and depth of sheets, if they are to be of any real value, must be made in a single granite body that is rather uniform in composition, texture, and structure. If it is jointed, the joints should have a reasonably uniform distribution. The Chelmsford granite, as exposed within the areas under consideration, meets all these requirements. Moreover, its main belt (Fig. 1), which lies athwart the direction of glacial ice movement, is bounded on the northwest by wholly different rock types, so that the approximate sources of large glacial boulders of this granite are seldom in doubt.

In view of the desired correlation between size of boulders and minimum depth of glacial erosion, we must determine the *minimum* rather than the *average* depth at which a sheet of specified thickness is encountered in the granite mass. This depth, unfortunately, cannot be referred to the preglacial surface, because no quarry in the region has been opened downward from such a surface. The southeast face of the H. E. Fletcher quarry in Westford, Massachusetts, however, does appear to be a section through a part of the granite body that has been less severely eroded than most. The sheets contained therein are listed in Table 1. Doubtless, additional thin sheets were present in preglacial time, but this is thought to be the nearest approach to a complete section obtainable in the district. The thicknesses of its

sheets have been plotted against the minimum depths at which they appear, and the resulting curve is shown in Figure 16.

TABLE 1

MEASURED SECTION OF SHEETS NEAR CENTER OF SOUTHEAST FACE, H. E. FLETCHER QUARRY, WESTFORD, MASSACHUSETTS

No. of Sheet	Thickness		Distance beneath Surface	
	Feet	Inches	Feet	Inches
1	1	5	0	0
2	0	10	1	5
3	0	4	2	3
4	0	7	2	7
5	0	6	3	2
6	0	7	3	8
7	1	1	4	3
8	0	5	5	4
9	0	11	5	9
10	1	1	6	8
11	1	5	7	9
12	1	2	9	2
13	0	5	10	4
14	1	4	10	9
15	1	4	12	1
16	1	10	13	5
17	0	8	15	3
18	1	10	15	11
19	2	7	17	9
20	0	7	20	4
21	1	10	20	11
22	1	8	22	9
23	0	8	24	5
24	4	4	25	1
25	2	9	29	5
26	2	6	32	2
27	8	2	34	8
28	10	0	42	10
29	11	4	52	10
30	12	11	64	2
31	9	6	77	1
32	6	7	86	7
33	8	2	93	2
34	17	3	101	4
35	31	1	118	7
Total	149	8	.....	.....

Detailed measurements were made in 139 quarries and on 44 natural exposures of Chelmsford granite to obtain data for statistical determination of the relations between sheet thickness and depth. The quarries were arbitrarily divided into two groups: "lee-side" quarries on a given hill are those located on its steep, irregular south and southeast sides, the positions of which, relative to the movement of glacial ice, resulted in the excavation of much rock by plucking; "standard" quarries are those located elsewhere on the hill. The amounts of material removed from those parts of the hill now occupied by standard quarries obviously may vary within certain limits, but the detailed measurements have shown that this variation is small enough to justify the averaging of minimum depths at which sheets of specified thicknesses are encountered. At a few places in standard quarries the depths of certain thick sheets are distinctly less than the average for sheets of such dimension; their attitudes with respect to the hill slopes, however, indicate the removal of unusually large amounts of rock from these places by glacial erosion.

TABLE 2

AVERAGED DATA FOR SHEETING IN STANDARD QUARRIES

Thickness of Sheet (Feet)	Average Minimum Depth (Feet)	Number of Observations
2	2.0	192
3	5.2	170
4	7.6	147
5	11.3	68
6	14.1	42
7	20.0	40
8	26.0	36
9	32.0	20
10	35.0	12
11	41.0	13
12	50.0	9
13	56.0	11
15	68.0	3
17	79.0	5
23	94.0	2
29–32	98.0	4

Table 2 contains the averaged data, and Figure 16 the corresponding curve, for the relations between thickness of

sheets and their respective average minimum depths in standard quarries. A similar curve for lee-side quarries also appears in Figure 16. It is clear that the stripping-away of granite by glacial erosion displaces the curves upward and to the left and that the ideal curve for a complete, unglaciated section would lie below and to the right of those in the diagram. All the curves are compound and undergo changes in slope at vertically consistent positions; briefly interpreted, they indicate a relatively large number of sheets of fairly uniform maximum thickness within the maximum-thickness ranges 0–4 feet and 9–15 feet. If the curves could be referred to a common datum, such as the preglacial surface, they probably would also show certain consistent depth ranges within which the sheets thicken very rapidly.

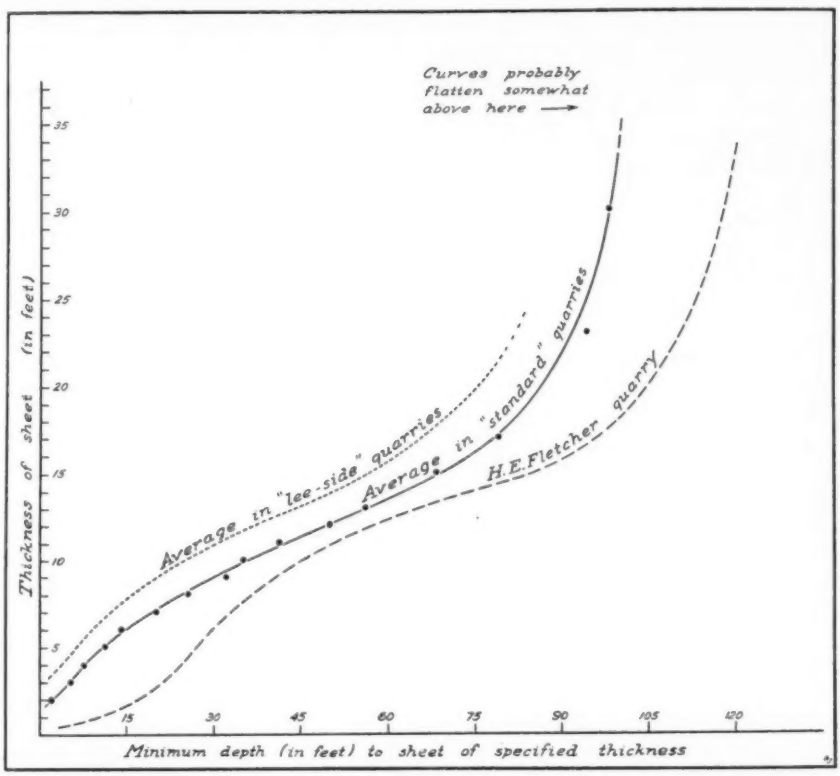

FIG. 16.—Graphic representation of the variation in thickness of sheets with their depth beneath the exposed rock surface.

GLACIAL BOULDERS

It is a simple matter to determine the minimum thickness of the sheet from which a glacial boulder of Chelmsford granite was derived, even if it is far from equidimensional. Foliation and mineralogic layering are readily recognizable, and their known consistency of strike and dip within the parent-mass permits

ready orientation of the boulder. Most of the larger boulders are so fresh and angular that remnants of the bounding sheet surfaces are still preserved; others permit only a minimum estimate of sheet thickness. The average standard quarry curve (Fig. 16) can be used to obtain the minimum depth of the sheet from which the boulder or block was torn. This is the depth below the present general surface of the hill (exclusive of heavily plucked lee-side surfaces) and is somewhat less than the total depth beneath the preglacial surface. Estimates of depth of erosion obtained from boulders by this method may therefore be regarded as somewhat conservative.

The surface of Oak Hill (Fig. 10) was once dotted with huge granite boulders, but most of them were split up into paving and constructional blocks and carried away to near-by towns many years ago. A few still remain intact, however, on a low ridge 0.3 mile south-southeast of the Morris Brothers quarry and on the hillside 0.3 mile north-northeast of the H. E. Fletcher quarry. Most were formerly parts of sheets at least 12 feet thick and consequently were derived from points on near-by hill slopes that were eroded to depths of at least 48 feet. Similar large boulders are very common on the north slope of Flushing Hill (Tyngsboro quadrangle), which is a drumlin, and on the south side of the granite hill immediately to the north.

The largest boulders seen in the entire region are scattered over the rough slopes west of Flushing Hill and north of Sought For Pond. Many were derived from sheets 15–20 feet thick. One huge, angular block represents a 27-foot sheet and must have been carried from a slope plucked to a depth of at least 95 feet; the numerous cliffs on the lee sides of adjacent granite hills support this view. Large boulders have been observed on Snake Meadow Hill, and a number of still larger ones have been quarried away by man. Remnants of a 15-foot sheet are present on the south side of Fletcher Hill (Fig. 8 and Ayer quadrangle), and boulders from sheets even larger lie on the slopes of the hills north and east of Sandy Pond (Ayer quadrangle).

Not only do the conclusions suggested by the above-mentioned representative boulder occurrences qualitatively support those resulting from the analysis of sheeting attitudes on individual hills, but the minimum amounts of glacial erosion estimated by each method are well within the same order of magnitude. As the position of the former, preglacial surface lies an unknown distance above the present surface of each hill, the total amount of glacial erosion cannot be estimated. If based on comparisons with the least-affected parts of the hill, however, certain minimum estimates can be made. These indicate that selective plucking of material from favorable places on granite hills, at least in the area herein discussed, may well have progressed to depths of 100 feet or more beneath the preglacial surface.

ACKNOWLEDGMENTS.—Professor W. E. Powers, of Northwestern University, and Mr. Max E. Willard, of Mount Holyoke College, made many helpful suggestions during the field season of 1941, and Drs. L. W. Currier, G. F. Loughlin, G. R. Mansfield, and F. E. Matthes, of the Geological Survey, discussed the theoretical aspects of the problem with the writer and kindly examined and criticized the manuscript. The writer is further indebted to L. W. Currier, who furnished several photographs illustrating critical relations of sheet structure, and to Frances H. Jahns, who assisted in the technical compilation of the manuscript.

THE RARER METALLIC CONSTITUENTS OF SOME AMERICAN IGNEOUS ROCKS. I

ERNEST B. SANDELL
University of Minnesota

SAMUEL S. GOLDICH
Agricultural and Mechanical College of Texas

ABSTRACT

This paper presents a study of the abundance and distribution of some of the rarer metallic constituents in igneous rocks. By means of chemical "trace" methods, 354 determinations have been made of metals, including molybdenum, beryllium, lead, zinc, cadmium, copper, nickel, and cobalt. The samples represent six regions: (1) the Michigan copper district, (2) Minnesota, (3) the St. Francois Mountains, Missouri, (4) the Llano uplift of central Texas, (5) the Clear Lake area, California, and (6) two New England localities.

The distribution of the minor elements is influenced by the major chemical constituents to a very appreciable extent. Apparently this is chiefly the result of isomorphous replacement of the major elements by the minor constituents in rock-forming minerals in accordance with the principles outlined by V. M. Goldschmidt. A number of relationships between minor and major constituents are indicated, although some are purely tentative.

Geologic factors are of great importance in determining the behavior of the minor, as well as of the major, chemical constituents; and differences brought out in the present study are interpreted to be the result of the different magmatic histories of the samples involved.

Estimates of the probable abundance of the minor elements in the crust of the earth are given. In addition to the determinations of the rarer metallic constituents, some new analyses of rocks and minerals are given. The chemical trace methods used are recommended to geologists and chemists interested in similar problems.

INTRODUCTION

The results of an investigation in the relatively unexplored field of geochemistry are presented in this paper. This study was initiated by the senior author in developing reliable chemical methods for the determination of certain rarer metallic constituents of silicate minerals and rocks. These methods have been applied to groups of samples from six regions in the United States, shown in Table 1. Preference has been given to samples for which bulk chemical analyses are available, but a number of composite samples are also included. Not shown in the summary are the determinations made on a number of minerals separated from certain of the igneous rocks.

A number of objectives were considered in undertaking this work, and it may be well to state these.

1. The study afforded an opportunity of testing out the applicability of chemical "trace" methods to problems in geology and in geochemistry, and, on the basis of the results obtained, these methods can be recommended. They are relatively simple and rapid; require no particularly expensive or unusual equipment; secure complete decomposition of a sample large enough to be representative; and, with correction for blanks on the reagents employed, are sufficiently accurate for present-day investigations. It is not the contention of the writers that the methods used here are in any way superior to spectrographic analyses. It should be emphasized rather that these methods give results that are in good agreement with the values reported by the most reliable workers using spectrographic methods.

2. Of considerable importance to the

present investigation are the possible relationships that exist between the rarer metals and the major chemical constituents usually determined in rock analysis. Along this line the pioneering efforts of V. M. Goldschmidt and his co-workers cannot be commended too highly. We are indebted to these investigators for most of our knowledge of the basic laws explaining the associations and the affinities governing the distribution of the elements in minerals and rocks and in meteorites.

3. Some new values for the abundance of the rarer metallic constituents are supplied for comparison with similar work by Europeans and with the earlier work by Clarke, Washington, Steiger, and others in this country.

4. Hopes were also entertained that the results might possibly have some bearing on fundamental problems in geology, and the junior author must accept responsibility for speculations relative to theories of origins of igneous rocks and of ore deposits.

The writers fully realize the limitations of the data numerically and, consequently, of the conclusions drawn from them. Nevertheless, it seemed desirable to record these findings at the present time, and for this purpose the paper has been divided roughly into three parts. In Part I the data are presented by regions. The geologic background is, of necessity, brief, but important references to the literature are included. In Part II the data are presented in a number of diagrams. Each element is discussed from the geochemical point of view. In Part III brief consideration is given to certain problems of interest to the petrographer and the economic geologist.

TABLE 1

SUMMARY OF SAMPLES AND NUMBER OF DETERMINATIONS

	Samples	Mo	Be	Pb	Zn	Cd	Cu	Ni	Co	Total
Michigan	26	.....	.....	9	24	.....	24	24	24	105
Minnesota	22	13	3	22	22	7	22	16	15	120
Missouri	7	1	1	7	7	.....	7	7	7	37
Texas	7	7	5	7	7	2	7	6	7	48
California	10	.....	.....	10	10	.....	10	.....	.....	30
New England	3	1	.....	3	3	.....	3	2	2	14
Total	75	22	9	58	73	9	73	55	55	354

METHODS OF ANALYSIS

All the methods used are colorimetric except the one for beryllium, which is fluorometric. These methods are briefly outlined.

MOLYBDENUM[1]

The rock powder was fused with sodium carbonate, and an aliquot of the filtrate from the leached melt representing 0.5 gram of sample was treated with hydrochloric acid, potassium thiocyanate, and stannous chloride to give the strongly colored thiocyanate of molybdenum in a lower-valence state for extraction with ether.

BERYLLIUM[2]

The sample (0.20 gm.) was fused with sodium hydroxide, the melt leached, and

[1] E. B. Sandell, "Determination of Chromium, Vanadium, and Molybdenum in Silicate Rocks," *Ind. Eng. Chem., Anal. Ed.*, Vol. VIII (1936), p. 339.

[2] Sandell, "Determination of Small Amounts of Beryllium in Silicates," *ibid.*, Vol. XII (1940), p. 674.

an aliquot of the filtrate treated with morin. The fluorescent solution was compared with similar standards in ultraviolet light. The residue from the first fusion was re-fused to recover any retained beryllium.

LEAD, ZINC, AND COPPER[3]

The sample (0.25 gm.) was decomposed with hydrofluoric and perchloric acids and the three metals extracted from an ammoniacal citrate solution with diphenylthiocarbazone (dithizone) in carbon tetrachloride. The extract was shaken with dilute (0.01 N) hydrochloric acid to transfer lead and zinc to the aqueous phase, leaving copper in the carbon tetrachloride. The latter was evaporated, the residue was ignited, and the resulting copper oxide was dissolved in hydrochloric acid, in which, after dilution, copper was determined by the mixed-color dithizone method. Lead and zinc were determined in suitable aliquots of the aqueous phase with dithizone in the presence of cyanide and thiosulphate, respectively, to prevent the reaction of other metals.

CADMIUM[4]

Dithizone was used for the separation and determination of cadmium. The method was made specific by carrying out the reaction in a strong sodium hydroxide solution.

NICKEL AND COBALT[5]

The sample (0.25–0.50 gm.) was decomposed with hydrofluoric and perchloric acids, and the nickel was extracted as the dimethylglyoxime compound with chloroform from an ammoniacal citrate solution. Cobalt was extracted as the dithizonate. Nickel was determined as nickelic dimethylglyoxime and cobalt with thiocyanate in acetone or amyl alcohol medium after suitable treatment of the extracts.

DIAGRAMS

Most of the samples used in this study had previously been analyzed for the major constituents, and it has been possible to correlate the major and minor constituents in a more quantitative fashion than has been done before. The variations of the heavy metals with the contents of major constituents are shown in a number of diagrams. It should be noted that it has been necessary to exaggerate, as well as to use different scales, to represent these variations. The amount of exaggeration will naturally affect the slope of the resultant line, and this should be kept in mind in comparing curves for different elements. In Figure 7 the percentages of copper, lead, and zinc have been recalculated to total 100 and have been plotted on the triangular diagram. Because of the small quantities involved, small absolute errors are large percentage errors. Thus the lead percentage may be shown as 10 per cent, but it might easily be 5 or 20 per cent of the total weight of the three metals. Figures 11, 12, and 13 are the well-known silica-variation diagrams.

The curves as drawn do not always strictly represent the data. It should be emphasized that further study and additional data are needed to evaluate the factors that result in scattering of the points. Certain trends and tendencies, however, are apparent, and these the writers believe are worthy of graphic presentation.

[3] Sandell, "Determination of Copper, Zinc, and Lead in Silicate Rocks," *ibid.*, Vol. IX (1937), pp. 464–69.

[4] Sandell, "Determination of Cadmium in Silicate Rocks," *ibid.*, Vol. XI (1939), p. 364.

[5] Sandell and R. W. Perlich, "Determination of Nickel and Cobalt in Silicate Rocks," *Ind. Eng. Chem., Anal. Ed.*, Vol. XI (1939), pp. 309–11.

PRESENTATION OF DATA

MICHIGAN

INTRODUCTORY STATEMENT

Representative samples of the material used by T. M. Broderick[6] in his study of the Keweenawan lavas of Michigan were generously made available to the writers for the present investigation of the distribution of the minor heavy metals in the Kearsarge and Greenstone flows. In addition, five samples were selected to obtain some information for the district as a whole. Samples Nos. 3156 and 3157 represent the felsite of Bare Hill and the felsite of Mount Houghton, respectively. The Mount Bohemia gabbro–gabbro aplite series includes three samples: No. 3161, gabbro aplite; No. 3163, an intermediate rock; and No. 3166, a basic phase. For details of sampling and of the petrographic characters of these samples the reader is referred to Broderick's paper.

DISCUSSION OF DATA

Copper, zinc, nickel, and cobalt were determined in all the samples and lead in seven. Composite samples prepared to represent the Kearsarge and the Greenstone flows were analyzed for lead, and these results are given as weighted averages in Table 2. The earlier determinations of copper published by Broderick have been included in the table. In these determinations the copper was extracted from samples of 3–4 grams by an aqua regia treatment. In Sandell's determinations complete decomposition of the samples was secured by use of hydrofluoric acid, and a higher degree of accuracy can be attributed to these figures. However, the two methods produced results that are remarkably alike, substantiating the findings of B. S. Butler and W. S. Burbank,[7] as well as of Broderick and C. D. Hohl,[8] that the copper occurs in the trap rocks of the Michigan copper district chiefly in the form of sulphides.

Indirect evidence of the close association of sulphur and copper is provided by the samples of the Kearsarge and Greenstone flows. In Figure 1 copper has been plotted against sulphur content, and the majority of the points fall close to a line representing the ratio of copper to sulphur in chalcopyrite. The presumption is strong that copper is present in most of the samples chiefly as chalcopyrite or, at least, was so originally. Sample No. 3132, representing the upper 116 feet of the Greenstone flow, contains an abnormally large amount of sulphur (0.08 per cent) and is not shown in the diagram. This high value brings the weighted average for the Greenstone to 0.023 per cent, whereas omission of this sample would reduce the average about one-half. Some of the samples have less sulphur than is demanded by the ratio 2S:Cu. This is especially true of sample No. 3113 of the Kearsarge and of sample No. 3140 of the Greenstone flow. In these samples the copper contents rise to maxima for the series, and the impression is gained that copper appropriates sulphur from the magma to form chalcopyrite as long as it is available in sufficient amounts and then separates out in forms containing less sulphur or no sulphur at all (native copper or possibly as a silicate in which the copper may replace ferrous iron).

Broderick introduced a type of "straight-line" diagram in which each chemical constituent in the various sam-

[6] "Differentiation in Lavas of the Michigan Keweenawan," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 503–58.

[7] "The Copper Deposits of Michigan," *U.S. Geol. Surv. Prof. Paper 144* (1929), p. 46.

[8] "Differentiation in Traps and Ore Deposition," *Econ. Geol.*, Vol. XXX (1935), p. 304.

ples is compared to the weighted average for this constituent for the flow as a whole. The variations are expressed in percentages above or below the weighted average. The necessary calculations have been made for the heavy metals, and the variations of nickel, cobalt, zinc, and copper with depth in the Kearsarge and in the Greenstone flows are shown in Figures 2 and 3. In both flows it is apparent that the variations of nickel and cobalt are closely related, as are zinc and copper variations; but the behavior of zinc and copper is diametrically opposed to that of nickel and cobalt. The variation of the relative percentages of the metals with depth is shown also in Figures 4 and 5. In the Kearsarge flow the percentages of nickel and cobalt tend to increase with depth to about the middle of the flow and then to decrease; zinc and copper tend to decrease with depth to

TABLE 2

HEAVY METALS IN KEWEENAWAN IGNEOUS ROCKS OF MICHIGAN

SAMPLE NO.	PER CENT					
	Cu*	Cu†	Zn†	Pb†	Ni‡	Co‡
Kearsarge flow:						
3112	0.006	0.008	0.011	.....	0.008	0.0025
3113	.016	.026	.012	.....	.009	.0032
3115	.005	.006	.0085	.....	.017	.0036
3117	.004	.005	.009	.....	.021	.0040
3119	.006	.0045	.009	.....	.023	.0040
3121	.011	.0095	.0135	.....	.021	.0043
3123	0.014	0.015	0.0125	.....	0.009	0.0038
Weighted average	0.009	0.0094	0.0114	0.0008§	0.017	0.0038
Greenstone flow:						
3132	0.015	0.010	0.009	<0.0005	0.021	0.0050
3134	.007	.0095	.009	.0006	.018	.0040
3136	.023	.024	.0175	< .0005	.004	.0030
3138	.011	.0115	.010	< .0005	.007	.0039
3140	.029	.030	.013	0.0007	.004	.0033
3142	.011	.012	.010	.....	.006	.0027
3144	.017	.014	.0095	.....	.007	.0039
3146	.012	.0185	.011	.....	.009	.0039
3148	.013	.011	.010	.....	.012	.0048
3150	.010	.0085	.0075	.....	.020	.0055
3152	.010	.0095	.0085	.....	.043	.0055
3154	0.008	0.011	0.0085	.....	0.029	0.0052
Weighted average	0.012	0.0121	0.0095	<0.0005§	0.0179	0.0045
Miscellaneous:						
3156	0.003	0.003	0.003	<0.0005	0.0006	0.0002
3157	.003	.0025	.0015	<0.0005	.0003	.0001
3161	.013	.013	.009	.....	.0008	.0012
3163	.010	.0145	.014	.....	.0046	.0048
3166	0.017‖	0.032	0.029	.....	0.0027	0.0040

* S. S. Goldich, analyst.
† E. B. Sandell, analyst.
‡ D. Smith and R. Nordgren, analysts.
§ Determined on a composite sample.
‖ Reported by Broderick as 0.014.

about the same point and then to increase. In Figure 2 it can be seen that the samples from the middle portion of the flow are above average in nickel and cobalt and below average in zinc and

The similarity of the variation curves for copper based on the data by Goldich and on those by Sandell should be noted. Of greater interest, however, is the fact that the variation trends of the heavy

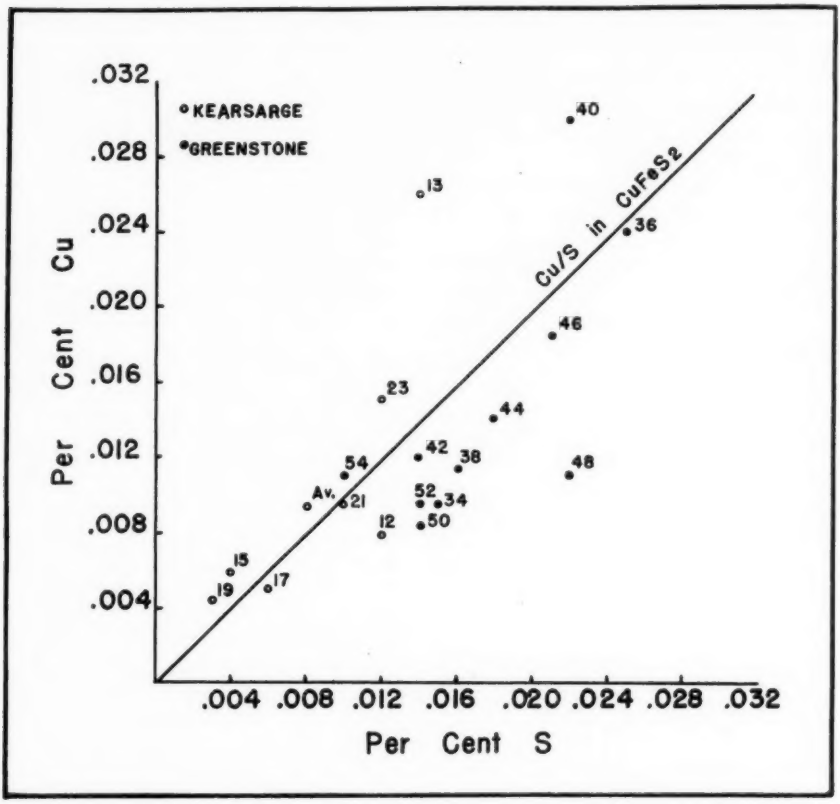

FIG. 1.—Variation of copper with sulphur in the Kearsarge and Greenstone flows, Michigan. The figures are the last two digits of Broderick's sample numbers.

copper. This distribution is probably due to the relatively rapid and approximately equal rates of cooling of the flow from two surfaces. In the Greenstone flow, although the distribution of the metals is not a regular one, there is a concentration of copper and zinc in the middle and upper portion of the flow and of nickel and cobalt in the lower portion.

metals closely follow the major constituents. Broderick divided the chemical constituents into two large groups suggestive of a more or less common behavior of the elements in each group. The first comprises SiO_2, Fe_2O_3, FeO, Na_2O, K_2O, TiO_2, P_2O_5, S, Cu, and MnO. Zinc can be added to this list and undoubtedly also lead, although the data

for this metal are incomplete. The second group includes Al_2O_3, MgO, and CaO, and to this list should be added nickel and cobalt.

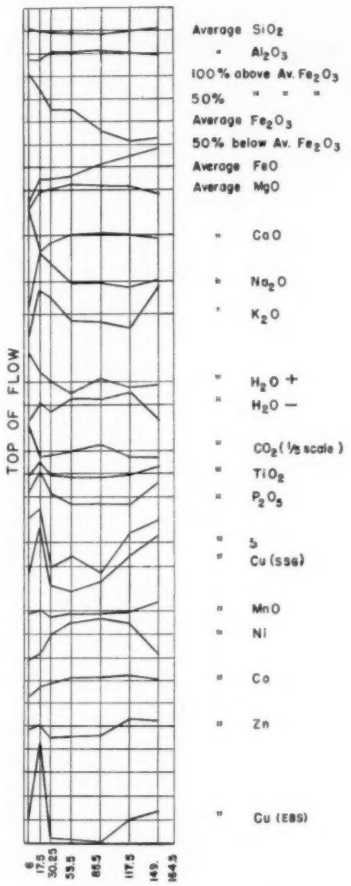

FIG. 2.—Broderick's diagram, showing variation of oxides with depth in the Kearsarge flow, Michigan. Variations of metals with depth have been added.

The variations of the chemical constituents are also shown in the normative minerals: olivine, hypersthene, diopside, anorthite, albite, orthoclase, magnetite, ilmenite, and apatite. On the whole, the distribution within the flow is what might be expected as a result of a rather limited differentiation controlled by fractional crystallization with crystal settling. Early crystallization of magnesium-rich minerals would tend to concentrate iron, the alkalis, silica, titania, sulphur, copper, zinc, lead, and manganese in the liquid phase along with the volatiles or mineralizers. Settling of these early crystals would produce fractionation of the magma. Broderick, however, has argued that a number of peculiarities in the distribution of the elements within the flow can be explained satisfactorily only by gaseous transfer.

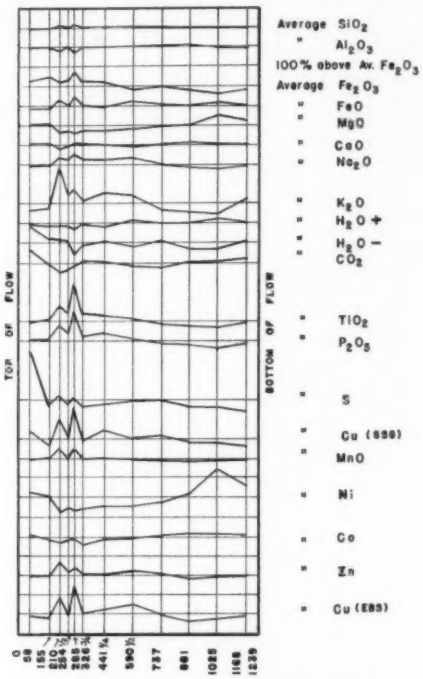

FIG. 3.—Broderick's diagram, showing variation of oxides with depth in the Greenstone flow, Michigan. Variations of metals with depth have been added.

At several horizons within the Green-

stone flow, layers or streaks of dolerite occur. Samples Nos. 3136 and 3140, plotted at 210 feet and 285 feet, respectively, represent such zones. These dolerite layers are said to be essentially horizontal, parallel to the upper and lower surfaces of the flow, and to persist laterally over extensive areas. The coarse texture of the dolerite indicates that the hyperfusibles were concentrated at these levels and probably were instrumental in their development. Reference to Figures 3 and 5 will show that notable concentrations of the constituents given in Broderick's first list occur in the dolerite layers. The specific gravity of these zones is appreciably above the rest of the series, reflecting the high content of mag-

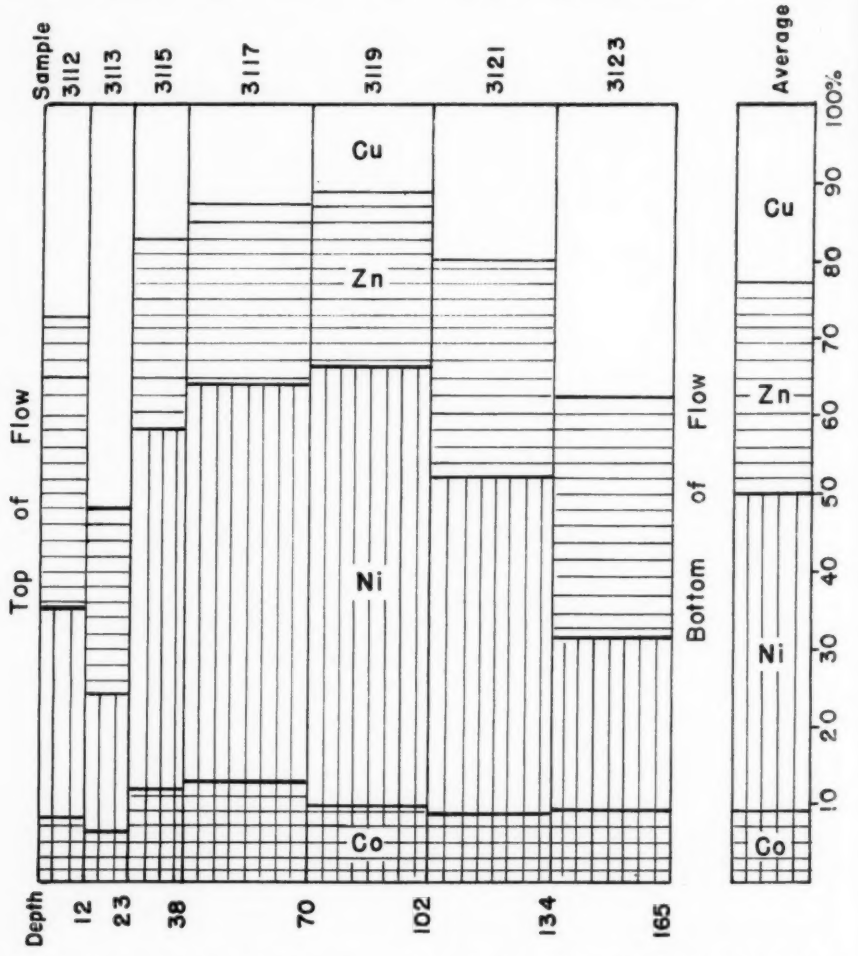

FIG. 4.—Variation of the relative percentages of Cu, Zn, Ni, and Co with depth in the Kearsarge flow, Michigan.

netite-ilmenite. It is chiefly for these reasons that Broderick concluded that their origin cannot be explained satisfactorily on the basis of crystallization-differentiation with crystal settling. Broderick also called attention to the correspondence of the elements concentrated in the dolerite streaks and in the upper

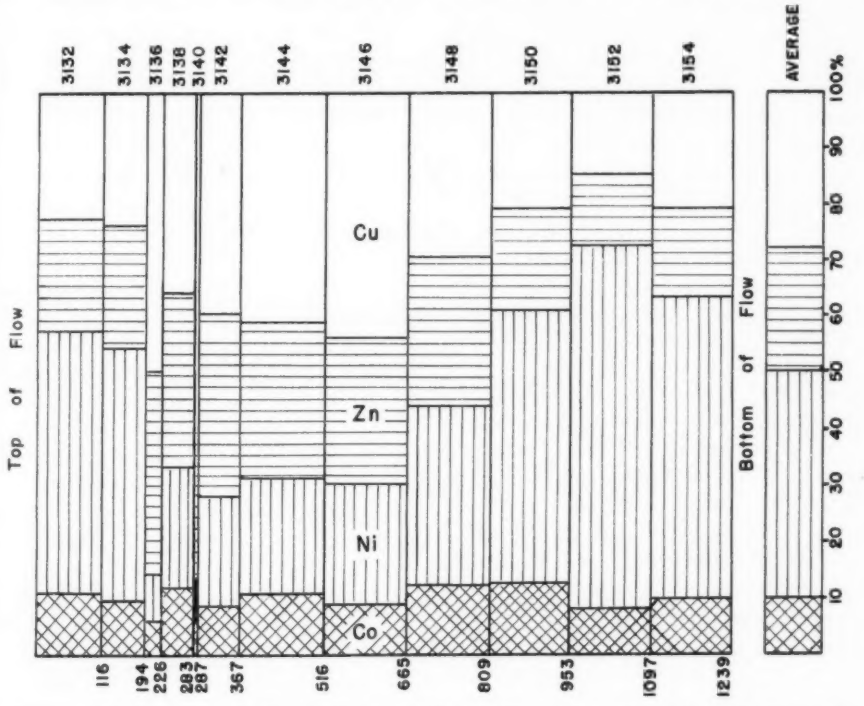

FIG. 5.—Variation of the relative percentages of Cu, Zn, Ni, and Co with depth in the Greenstone flow, Michigan.

portions of the flows to the list of elements that, according to N. L. Bowen,[9] might be most prominent in the vapor phase from boiling pegmatitic liquid. Bowen's list includes hydrogen, oxygen, chlorine, silicon, fluorine, sulphur, boron, potassium, sodium, iron, titanium, aluminum, zinc, lead, copper, silver, and a number of others. The alkaline earths would not be expected to be abundant in the gas phase. Broderick notes that the behavior of alumina in the Michigan flows is an exception and refers to the suggestion by C. N. Fenner[10] that the strong tendency of $AlCl_3$ to react with H_2O to form oxide would tend to keep aluminum out of the gas phase. Variation of the normative plagioclase in the Greenstone flow indicates that the more calcic plagioclase accompanied the early ferro-magnesian minerals, and, as a result, the variation of Al_2O_3 with depth

[9] "The Broader Story of Magmatic Differentiation, Briefly Told," *Ore Deposits of the Western States* (Amer. Inst. Min. Met. Eng., 1933), p. 120.

[10] "Pneumatolytic Processes in the Formation of Minerals and Ores," *Ore Deposits of the Western States* (1933), p. 84.

might be expected to follow that of MgO and CaO.

Fenner called attention to the high vapor pressures of the chlorides of some of the metals, including zinc, cadmium, lead, nickel, tin, and bismuth, as well as iron and aluminum. If the distribution of iron, copper, zinc, etc., in the flows is to be explained by gaseous transfer, it might be expected that similar variation should be shown by nickel; but this element is closely related to MgO in such a manner as to indicate clearly that, although the concentration of the mineralizers in certain zones may have produced differentiation within the flows, this process is nevertheless closely tied up with the fractional crystallization of the magma.

T. L. Walker,[11] in studying the variation of specific gravity along sections across the Sudbury mass, emphasized the fact that the heaviest rocks lie in the "*upper* part of the norite and in the lower part of the transition" to the micropegmatite rock. In the process outlined by Walker to account for this distribution, the volatile constituents are considered to have been effective in reducing the viscosity of the magma fluid in the zones now occupied by the heaviest rocks. The dominant factor in the process is regarded as having been the "orderly crystallization and sinking of heavy minerals" in the crystallization of the originally homogeneous liquid.

Broderick admits the difficulty encountered in explaining the horizontal attitude of the dolerite layers. He notes also that the olivine content of the Greenstone flow does not increase gradually with depth to a certain point and then decrease but, rather, that notable concentrations of olivine occur at several levels. These facts are suggestive of stratification in the liquid during crystallization. Although more than a single mechanism may have acted to produce the differentiation in the Michigan flows, fractional crystallization must be recognized as a fundamental process. It should be emphasized that the variations of nickel and cobalt closely follow the trends of MgO and CaO, whereas zinc and copper appear to be related to the distribution of iron. Variations of the heavy metals with the major constituents are shown in diagrams, to which further reference will be made.

[11] "Magmatic Differentiation as Shown in the Nickel-Intrusive of Sudbury, Ontario," *Contr. Can. Min.*, No. 38 (1935), pp. 23–31.

MINNESOTA

INTRODUCTORY STATEMENT

Twenty-two samples representing all sections of the state were studied. Locations are given in Table 3 and results in Table 4. Ten of the samples represent the material used in the bulk chemical analysis. Three new analyses are quoted in Table 5. Four chemical analyses, all by Frank F. Grout, were taken from the literature, and references are given in Table 3.

DISCUSSION OF DATA

The basic igneous rocks from the Keweenawan of Michigan and Minnesota are much alike in their metal content. The acid igneous rocks of Michigan are not sufficiently represented for comparison. It appears likely that there is a relationship between the igneous rocks of these regions and the Lake Superior copper deposits. Samples Nos. 17–22 represent facies of the Endion sill which is overlain by a rhyolite flow, sample No. 22. These samples have been described recently by G. M. Schwartz and A. E. Sandberg,[12] who studied the chemical and mineralogical variations with depth in a

[12] "Rock Series in Diabase Sills at Duluth, Minnesota," *Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 1135–72.

TABLE 3

LOCATION OF SAMPLES FROM MINNESOTA

Sample No.	Rock	Location	Reference
1	Rhyolite	Along Devil's Track River, Cook County; Sec. 11, T. 16 N., R. 1 E.	
2	Granite gneiss	Cold Spring Granite Company quarry, Morton	*Jour. Geol.*, Vol. XLVI (1938), p. 22, anal. No. 1
3	Granite	Small quarry about 7 miles east of Malmo; southern Aitkin County	New analysis, Table 5, No. 3
4	Granite	Northern Kanabec County; Sec. 1, T. 42 N., R. 24 W.	
5	Granodiorite	Quarry at Warman, Kanabec County; SE ¼ Sec. 6, T. 41 N., R. 23 W.	*U.S. Geol. Surv. Bull. 663* (1918), p. 141
6	Granite	Quarry south of Fish Lake; about 1 mile west of Pierz, Morrison County; SE ¼ Sec. 13, T. 40 N., R. 31 W.	*Ibid.*, p. 137
7	Granodiorite	"St. Cloud gray" granite, St. Cloud	*Ibid.*, p. 52
8	Orthoclase gabbro	Duluth	
9	Diabase	Columnar diabase in Grand Marais Harbor; Sec. 14, T. 61 N., R. 1 E.	New analysis, Table 5, No. 9
10	Greenstone	Winton	
11	Diabase	Taylor's Falls	*Jour. Geol.*, Vol. XVIII (1910), p. 644, anal. No. 2
12	Gabbro	Along boulevard above cement mill; Duluth	
13	Gabbro	Fairmont Park, Duluth (Kingston Creek at railroad)	*Ibid.*, Vol. XXVI (1918), p. 646, anal. No. 1
14	Diabase	Diabase Hill, Lake County; Sec. 1, T. 53 N., R. 10 W.	*Ibid.*, Vol. XLVI (1938), p. 46, anal. No. 11
15	Syenite	Along Gunflint Trail, Cook County; NW ¼ Sec. 7, T. 64 N., R. 1 E.	*Minn. Geol. Surv. Bull. 20* (1925), p. 89
16	Diabase	Shore of Lake Superior; 2½ miles east of Grand Marais	
17	Diorite	Williams Quarry, Little Falls, Morrison County	New analysis, Table 5, No. 17
18	Diabase	Endion sill, Duluth	*Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 1135–72, Table 1, anal. No. 1
19	Diabase	Endion sill, Duluth	*Ibid.*, anal. No. 3
20	Red rock	Endion sill, Duluth	*Ibid.*, anal. No. 4
21	Red rock	Endion sill, Duluth	*Ibid.*, anal. No. 6
22	Rhyolite	Above Endion sill, Duluth	*Ibid.*, anal. No. 7

number of sills. Two distinct rock types are said to constitute the Endion sill—diabase and red rock. The chemical gradations from the base to the top of the Endion sill are from diabase toward granite, and in diagrams and in variation curves projections of the trends shown in the sill reach points representing the rhyolite into which the sill is supposedly intrusive.

TABLE 4*

HEAVY METALS IN MINNESOTA IGNEOUS ROCKS

SAMPLE NO.	PER CENT					
	Mo	Pb	Zn	Cu	Ni	Co
1	0.0004	0.0012	0.006	0.006	0.0004	<0.0001
2	< .0001	.0022	.005	.002	.0008	.0004
3	.0002	.0016	.005	.0015	.0011	.0005
4	.....	.0024	.009	.0035	.0011	.0003
5	< .0002	.0016	.006	.003	.0010	.00045
6	.....	.0027	.007	.014	.0008	.00045
7	.0001	.0022	.006	.004	.0020	.0007
8	.....	.0004	.004	.007	.0050	.0016
9	.0002	.0023	.016	.024	.0040	.0026
10	.....	.0002	.014	.007	.0070	.....
11	.0001	.0005	.015	.023	.0160	.0042
12	.0001	.0007	.010	.013	.0240	.0030
13	.....	.0008	.010	.018	.....	.....
14	.....	.0005	.008	.012	.0160	.0028
15	.0005	.0009	.022	.022	.0006	.0015
16	.....	.0015	.012	.028	.0200	.0045
17	< .00005	.0008	.010	.013	0.0060	0.0021
18	.00015	.0002	.014	.021	.....	.....
19	.....	.0022	.023	.017	.....	.....
20	.00030	.0018	.017	.0065	.....	.....
21	.....	.0012	.021	.010	.....	.....
22	0.0003	0.0019	0.006	0.0005	.....	.....

* E. B. Sandell, analyst.

A number of hypotheses was considered by Schwartz and Sandberg to account for the differentiation in the sills. They concluded that the most acceptable of these is differentiation following intrusion of a magma probably similar in composition to that of the Duluth lopolith. The possible mechanisms of the differentiation were not analyzed in detail, although the processes of crystal settling, liquid immiscibility, and concentration of the mineralizers in the upper portions of the sills were suggested. The authors noted some similarity between the trend of differentiation in the Minnesota sills and that of the lavas described by Broderick. In both occurrences differentiation has been toward a siliceous, highly ferruginous, alkalic rock. Broderick suggested that the mechanism producing the differentiation is a process of gaseous transfer. Although specific mention of gaseous transfer is not made by Schwartz and Sandberg, they give some emphasis to the probable effectiveness of the mineralizers.

TABLE 5

RECENT CHEMICAL ANALYSES OF IGNEOUS ROCKS FROM MINNESOTA

	3	9	17
SiO_2	71.19	52.70	48.14
Al_2O_3	15.00	14.47	17.45
Fe_2O_3	0.67	7.44	3.73
FeO	1.49	5.55	6.72
MgO	0.81	3.70	6.28
CaO	1.83	8.01	9.92
Na_2O	3.64	3.19	2.39
K_2O	4.57	1.14	1.95
H_2O+	0.68	0.68	1.44
H_2O-	0.03	0.48	0.12
TiO_2	0.30	1.76	0.57
P_2O_5	0.07	0.25	0.22
MnO	0.01	0.24	0.17
BaO	n.d.	0.05	0.10
S	0.02	0.02	0.04
Total	100.31	99.68	99.24

3. Granite, southern Aitkin County; E. B. Sandell, analyst.

9. Diabase, Grand Marais Harbor; E. D. Burr, student analyst.

17. Diorite, Williams Quarry, Little Falls; Donald Smith, student analyst.

Differentiation of the sills into diabase and granite facies is probably closely related to the concentration of mineralizers in the upper portion of the sills; the mineralizers played a considerable role especially in the formation of the red rock with micropegmatite as an important constituent and possibly also in the crystallization of considerable magnetite-ilmenite in the acidic facies.[13]

[13] *Ibid.*, p. 1169.

MISSOURI

INTRODUCTORY STATEMENT

Early theories advanced to explain the origin of the lead and zinc deposits of Missouri focused attention on the metal content of the igneous rocks of the St. Francois Mountains. Analyses by J. D. Robertson were published in 1894 by Arthur Winslow[14] and have been cited by numerous writers since that time. Two of the samples tested by Robertson are duplicated: the granite at Graniteville and the diabase at Skrainka. The first of these has been described in detail by Carl Tolman and Goldich.[15] The remaining six samples, together with the unpublished chemical analyses, were generously supplied by Professor Tolman, of Washington University, St. Louis.

DISCUSSION OF DATA

Locations of samples and the results obtained are given in Table 6. The percentage of copper in the granite at Graniteville given by Robertson (0.010 per cent) is four times as great as that obtained by Sandell. This value, as well as Robertson's figure for lead (0.0065 per cent) in the diabase at Skrainka, is considered to be too high; but for the remaining determinations the values by Robertson are in tolerable agreement with the newer data, and for zinc and copper in the diabase the agreement is remarkably good. Considerable differences in the metal contents of the granites are noted. Lead ranges from 0.0009 to 0.0045 per cent and zinc from 0.0015 to 0.0085 per cent. These differences, in part, reflect similar ranges for the major chemical constituents. The heavy metals found in the soda-rich granitic dike rock cutting the diabase at Skrainka are approximately one-tenth of the percentages found in the diabase, but the high nickel and cobalt contents suggest a close genetic relationship between the two. If such is the case, the magmatic derivation of this rock is probably not comparable to that of the granites in the series, and points for the dike rock (No. 7) may well be expected to deviate from the curves in the various diagrams in which the Missouri data have been plotted.

TABLE 6*

HEAVY METALS IN MISSOURI IGNEOUS ROCKS

Sample No.†	Per Cent					
	Mo	Pb	Zn	Cu	Ni	Co
1	0.0002	0.0027	0.0085	0.0008	0.0003	<0.0001
2	.....	.0009	.0025	.000	.0002	.0004
3	.....	.0045	.0015	.0025	.0003	<.0001
4	.....	.0020	.021	.001	.0009	.0008
5	.....	.0013	.009	.000	<.0001	<.00005
6	.....	.0005	.013	.0065	.020	.0055
7	.....	<0.0005	0.0015	<0.0005	0.0030	0.0006

* E. B. Sandell, analyst.

† Samples as follows:

1. Granite near Mine Lamotte.
2. Granite near Holladay Mountain.
3. Granite at Graniteville.
4. Rhyolite at Iron Mountain.
5. Rhyolite at Skrainka.
6. Olivine diabase at Skrainka.
7. Soda-granite dike cutting diabase at Skrainka.

[14] "Lead and Zinc Deposits," *Mo. Geol. Surv.*, Vol. VII (1894), p. 480.

[15] "The Granite, Pegmatite, and Replacement Veins in the Sheahan Quarry, Graniteville, Missouri," *Amer. Min.*, Vol. XX (1935), pp. 229–39.

CENTRAL TEXAS

INTRODUCTORY STATEMENT

The Llano region or Llano uplift of central Texas includes all of Llano County and parts of Burnet, Blanco, Gillespie, Mason, McCulloch, San Saba, and Lampasas counties. This is a region of igneous rocks, predominantly granitic, intruded into folded metamorphics—gneiss schist, marble, quartzite, and others. Sedimentary rocks are chiefly of early Paleozoic and Lower Cretaceous (Comanche) age. These flank and overlap the pre-Cambrian metamorphic and igneous series. The district is commonly called

the "central mineral" region, and many prospects reveal mineralization in a number of metals. Tin, molybdenum, bismuth, and rare-earth minerals are genetically related to the igneous rocks. Certain iron, copper, and other prospects may be connected with the intrusives. Lead and zinc mineralization in the Lower Paleozoic sediments is obviously of a younger period, and the relation of these to magmatic action is obscure. The general geology and the prospects of the central mineral region have been described by Sidney Paige[16] and by E. H. Sellards and C. L. Baker.[17] A bismuth-molybdenum prospect in southeastern Llano County has been described recently by H. B. Stenzel and V. E. Barnes.[18] Chemical analyses and petrographic descriptions of the samples have been published.[19]

DISCUSSION OF DATA

Results of the determinations of the heavy metals in the central Texas granites are given in Table 7. Biotite separated from the granite at Town Mountain contained zinc, 0.037 per cent, and copper, 0.006 per cent. The heavy minerals separated from the dike rock (llanite) contained zinc, 0.11 per cent. This separate was composed chiefly of magnetite and biotite. The data show a close relationship between minor and major constituents. Zinc and copper appear to be influenced by the iron content; nickel and cobalt, by magnesia. The tendency for molybdenum and lead to be concentrated in the highly siliceous and alkalic differentiates is shown by the Texas series as a whole and specifically by the relations between the granite of Petrick's Quarry and the aplite dike, which represents a late differentiate of the granitic magma.

TABLE 7*

HEAVY METALS IN CENTRAL TEXAS GRANITES†

SAMPLE No.	PER CENT					
	Mo	Pb	Zn	Cu	Ni	Co
1	0.0001	0.0013	0.007	0.0015	0.00030	0.00055
2	.0002	.0022	.012	.0015	.00019	.0003
3	.0003	.0030	.009	.0010	.00009	.00015
4	.0002	.0013	.005	.0005	.00017	.0003
5	.0007	.0020	.011	.0007	.00026	.0001
6	.0004	.005	.004	.0005	0.00011	.00005
7	0.0004	0.0017	0.0015	0.0003	n.d.	0.00005

* E. B. Sandell, analyst.

† The granites are classified as follows:

Town Mountain granites
1. Granite of Town Mountain
2. Granite of Petrick Quarry
3. Granite of Granite Mountain

Sixmile granite
4. Cassaday granite

Miscellaneous
5. Granite porphyry (llanite) at Babyhead
6. Bear Mountain granite
7. Aplite of Petrick Quarry

CALIFORNIA

INTRODUCTORY STATEMENT

The writers are indebted to Dr. C. A. Anderson, of the University of California, for permission to use a series of volcanic rocks from the Clear Lake area, California. These rocks have been discussed in some detail in a paper by C. A. Anderson,[20] to which the reader is referred.

DISCUSSION OF DATA

Copper, lead, and zinc were determined for the series (Table 8) which, although representing a restricted silica range—56–76 per cent—is of special in-

[16] "Llano-Burnet, Texas," *U.S. Geol. Surv. Folio 183* (1912).

[17] "The Geology of Texas," *Univ. Tex. Bull. 3401* (1934).

[18] "A Bismuth-Molybdenum Prospect (Kiam Prospect) of Llano County, Texas," *Univ. Tex. Bull. 3945* (1940), pp. 911–22.

[19] Goldich, "Evolution of the Central Texas Granites," *Jour. Geol.*, Vol. XLIX (1941), pp. 697–720.

[20] "Volcanic History of the Clear Lake Area, California," *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), pp. 629–64.

terest, because it is the most complete volcanic series investigated. In general, these rocks gave the least scattering of points in the various diagrams attempted, so that the curves representing the series are subject to a minimum of interpretation and are useful, therefore, as a comparative measure of the trends for similar constituents in other groups of rocks.

TABLE 8*

HEAVY METALS IN IGNEOUS ROCKS FROM THE CLEAR LAKE AREA, CALIFORNIA

Sample No.†	Rock	Per Cent		
		Pb	Zn	Cu
1....	Olivine basalt	0.0008	0.0075	0.0035
2....	Augite andesite	.0010	.0055	.0015
3....	Olivine andesite	.0007	.007	.001
6....	Pyroxene rhyodacite	.0011	.0045	.001
7....	Olivine dacite	.0012	.006	.002
8....	Hypersthene dacite	.0016	.0045	.001
9....	Biotite hornblende rhyodacite	.0016	.004	.0015
10....	Silicic pyroxene dacite	.0014	.004	.0015
11....	Biotite rhyolitic pumice	.0020	.003	.001
13....	Rhyolitic obsidian	0.0020	0.0035	0.001

* E. B. Sandell, analyst.

† Sample numbers refer to *Bull. Geol. Soc. Amer.*, Vol. XLVII (1936), p. 640, Table 1.

In the series of chemical analyses published by Anderson, three older analyses were taken from G. F. Becker.[21] Two of these report nickel equivalent to 0.32 and 0.16 per cent. These results are contradictory to the trends disclosed in the present investigation and are certainly erroneous. Approximate determinations made by L. Gullings on samples Nos. 1 and 7 gave 0.03 and 0.0024 per cent of nickel, respectively. These values are in keeping with the curve showing the variation of nickel with MgO (Fig. 9), the MgO values for these samples being 8.88 and 3.13 per cent, respectively. Analyses of Missouri granites[22] likewise report the equivalents of 0.11 and 0.16 per cent of nickel. These values could not be duplicated in analytical work carried on at Washington University, St. Louis, in 1933, and the present work fully substantiates the findings.

[21] "Geology of the Quicksilver Deposits of the Pacific Slope," *U.S. Geol. Surv. Mono. 13* (1888).

[22] F. W. Clark, "Analyses of Rocks and Minerals," *U.S. Geol. Surv. Bull. 419* (1910), p. 40.

NEW ENGLAND

INTRODUCTORY STATEMENT

Only two rocks from eastern United States have been studied, and these are included chiefly because they reveal some interesting facts about the distribution of the heavy metals. These rocks are the well-known Medford diabase from Massachusetts and a granite from the White Mountain district of New Hampshire. Descriptions of the Medford diabase indicate that a certain amount of differentiation has taken place. Two facies are represented in analyses Nos. 1 and 2 (Table 9), the latter being more silicic and containing some micropegmatite interstitial to and replacing the plagioclase.

DISCUSSION OF DATA

Although the sulphur contents of the two samples of the Medford diabase are about the same, there are notable differences in the heavy-metal contents. The granophyric phase contains more lead and zinc than the normal diabase but less copper, cobalt, and nickel. The relatively low copper content is of the order of the Skrainka diabase of Missouri. The average of the two samples, 0.0045 per cent copper, is much below the average of 0.016 per cent for the basic rocks of the Michigan copper district and of 0.015 per cent for the basic rocks of Minnesota. Even more striking is the apparent de-

ficiency in nickel compared to the igneous rocks in the same silica range from the central part of the United States.

TABLE 9

CHEMICAL ANALYSES OF NEW ENGLAND ROCKS AND MINERALS

	1	2	3*	4*	5
SiO_2	47.59	51.44	74.36	45.63	46.56
Al_2O_3	14.78	15.67	12.99	2.52	2.48
Fe_2O_3	4.39	2.25	0.70	7.47	6.24
FeO	9.11	8.37	1.47	27.17	27.27
MgO	4.28	2.09	0.10	0.76	1.35
CaO	9.06	6.31	0.35	5.56	6.15
Na_2O	3.36	4.42	4.60	4.19	4.17
K_2O	1.18	1.91	5.03	1.09	1.37
H_2O+	1.35	1.67	0.14	1.24	1.27
H_2O-	0.24	0.41	0.02	0.00	n.d.
TiO_2	3.55	1.95	0.19	2.88	1.83
P_2O_5	0.42	0.97	0.02	.....	.....
MnO	0.17	0.18	0.05	1.02	1.08
CO_2	0.65	2.14	.....	.....	.....
S	0.13	0.12	.....	.....	.....
F	.....	.....	p.n.d.	0.73†	n.d.
Total	100.26	99.90	100.02	100.26	99.77
$O \equiv S, F$	0.05	0.05	.....	0.31	.....
	100.21	99.85	100.02	99.95	99.77
Cu‡	0.0055	0.0035	0.001	0.002	.....
Pb	<0.0005	0.0005	0.0007	0.0010	.....
Zn	0.010	0.012	0.008	0.16	.....
Co	0.0036	0.0020	.....	.....	.....
Ni	0.0020	0.0005	.....	.....	.....
Mo	0.00015	.....	.....	.....	.....

* Analyses made in the department of geology, Washington University, St. Louis, 1934.

† Determination by R. B. Ellestad.

‡ All heavy-metal determinations by E. B. Sandell.

1. Medford diabase from an abandoned quarry. Sp. gr. 25°/4°, 2.945. Essentially normal diabase. Labradorite (An_{62}), augite, biotite, magnetite, apatite are primary minerals. Uralite chlorite and a little carbonate and pyrite are alteration products. A little quartz appears to be related to the carbonate and may have been introduced. S. S. Goldich, analyst (*Jour. Geol.*, Vol. XLVI [1938], p. 40).

2. Relatively fresh diabase opposite 93 Governor's Avenue, Medford, Mass. Sp. gr. 24°/4°, 2.80. Granophyr diabase containing labradorite (An_{51}), augite, biotite, quartz, and orthoclase in graphic intergrowth. Secondary products include abundant uralite, sericite, chlorite, epidote, carbonate, and a little pyrite. S. S. Goldich, analyst (*Jour. Geol.*, Vol. XLVI [1938], p. 40).

3. Medium-grained, light-gray granite from Devil's Slide, Percy quadrangle, New Hampshire. The microscopic texture is distinctly hiatal. Large crystals of perthite and alkalic amphibole, with small anhedral quartz and silicic plagioclase constituting intersertal material. Approximate mode: feldspar (mainly perthite), 70 per cent; quartz, 24 per cent; hornblende, 5 per cent; accessory apatite, fluorite, zircon, magnetite, 1 per cent. S. S. Goldich, analyst.

4. Amphibole separated from Devil's Slide granite by R. I. Dickey. Sp. gr. 24°, 3.45. Optical determinations by Dickey: *alpha*, 1.692; *beta*, 1.698; *gamma*, 1.710; $Z \wedge c$, 16°. S. S. Goldich, analyst. Fluorine determination by R. B. Ellestad.

5. Hornblende from syenite (19247), in Moore Brook at elevation 2,000 feet, Percy quadrangle. Approximately 3.5 miles southwest of Devil's Slide. F. A. Gonyer, analyst. Optical data given by Chapman and Williams: *alpha*, 1.688; *beta*, 1.699; *gamma*, 1.704; $Z \wedge c$, 25° (*Amer. Min.*, Vol. XX [1935], pp. 512–13).

The ratio of nickel to cobalt in basic rocks approaches 3:1. In the Medford diabase there is a reversal of this relationship, with cobalt exceeding nickel. The cobalt and nickel variation diagrams afford some explanation for this behavior. Plots of these elements against silica indicate that the percentage of nickel can be expected to fall off much more rapidly than that of cobalt with increasing silica content. Similarly, in plots of these metals against MgO, the percentage of nickel increases slowly with increasing MgO in the range up to 4 per cent. Above this point, however, nickel mounts rapidly with increasing magnesia. In contrast, the cobalt-magnesia relationship is a more constant one, suggesting a straight-line relationship. For their MgO contents, the samples of the Medford diabase appear to contain a slight excess of cobalt and small deficiencies of nickel. The deviations, however, may well be within the experimental error of the determinations.

M. P. Billings[23] has given the name "White Mountain magma series" to a group of rocks in the White Mountain district of New Hampshire. These rocks are characterized by their alkaline affinities. The granite represented in analysis No. 3 (Table 9) belongs to this series. The sample was collected by R. I. Dickey,[24] who described the outcrop as a small mass on the southeastern side of Devil's Slide about half a mile northeast of the village of Stark, New Hampshire. Copper and zinc contents of the granite are similar to the averages for these metals in the silicic rocks of central Texas and of Minnesota; however, the lead content is notably lower. Of interest is the distribution of the heavy metals in the

[23] "Paleozoic Age of the Rocks of Central New Hampshire," *Science*, Vol. LXXIX (1934), pp. 55–56.

[24] "Geology of the Devil's Slide, New Hampshire" (Master's thesis, Washington University, St. Louis, 1934).

minerals of the granite. Copper, lead, and zinc have been determined in analyzed hornblende separated from the granite by Dickey. The amphibole is remarkably similar in composition to an analysis (No. 5, Table 9) given by R. W. Chapman and C. R. Williams[25] of sodic hornblende from syenite outcropping in Moore Brook less than 4 miles southwest of Devil's Slide. The hornblende is intermediate in composition between hedenbergite from syenite and riebeckite from granite, as is indicated by analyses of these minerals given by Chapman and Williams. The sodic hornblende may represent a reaction product in the evolution of the riebeckite from hedenbergite. Chemical and mineralogical data indicate that 5 per cent is a fair estimate of the abundance of the amphibole in the Devil's Slide granite. By using this figure, it is found that all the zinc in the granite can be accounted for by the amphibole, but only 7 per cent of the lead and 10 per cent of the copper. These metals must be present either in other silicates (feldspars) or in traces of sulphides. The affinity of zinc for ferrous iron is clearly brought out.

[*To be concluded*]

[25] "Evolution of the White Mountain Magma Series," *Amer. Min.*, Vol. XX (1935), pp. 512–15.

MAFIC AND ULTRAMAFIC ROCKS OF THE BAIE VERTE AREA, NEWFOUNDLAND[1]

KENNETH DE P. WATSON
Princeton University

ABSTRACT

The paper discusses the field relations, petrography, and chemical compositions of a group of igneous rocks characteristic of geosynclinal belts: namely, greenstone, ultramafics, and gabbro, which occurs in the northeastern extremity of the Appalachians in the vicinity of Baie Verte, Newfoundland. The prevalent mineral assemblages of the greenstone are:

1. Actinolite-(chlorite)-albite-epidote-quartz
2. Chlorite-(actinolite)-albite-epidote-quartz
3. Chlorite-calcite-albite-epidote-quartz

Adjacent to a large quartz-diorite intrusive, the greenstone has been metamorphosed to the amphibolite facies characterized by hornblende, oligoclase, and biotite. Concentric structures in chert lenses associated with the greenstone suggest colloidal origin. The molecular ratio of Mg /Fe of the serpentinized harzburgite is within the range typical of the primary ultramafic magma series of Hess. The alterations and problems of correlation of the ultramafics are briefly considered. Discussion of pseudostratified metagabbro, its pegmatite facies, and alterations to zoisite-quartz and zoisite-prehnite assemblages, etc., is included. Small sills and dikes of mafic gabbro, diorite, porphyrite, and kersantite are described.

INTRODUCTION

The Baie Verte area is situated on a large peninsula between White Bay and Notre Dame Bay on the northern coast of Newfoundland, 50° N. lat., 56° W. long. (Fig. 1).

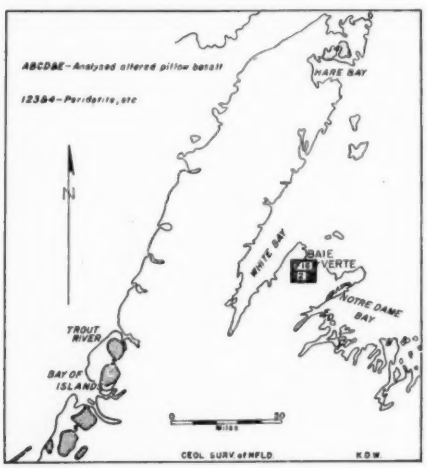

FIG. 1.—Index map of northwestern Newfoundland showing the position of the Baie Verte area.

Greenstones and associated ultramafic and gabbro intrusives are characteristic igneous constituents of the great deformed geosynclines throughout the entire world.[2] This group of rocks is well represented in the northeastern extremity of the Appalachian geosynclinal belt and was studied by the writer in the vicinity of Baie Verte.[3]

In common with the rest of Newfoundland, and the Appalachian mountain system in general, the structural trends in the area are northeast (Fig. 2). No fossils have been found in the rocks of this region and, therefore, correlation has been based on lithology.

The oldest rocks of the area, the Fleur-

[1] *Princeton University Contribution to the Geology of Newfoundland*, No. 21. Published with the permission of the government geologist of Newfoundland.

[2] Walter H. Bucher, *The Deformation of the Earth's Crust* (Princeton: Princeton University Press, 1933), pp. 268–73.

[3] Kenneth De P. Watson, "Geology and Mineral Deposits of the Baie Verte-Mings Bight Area," *Newfoundland Geol. Surv. Bull.* (to be published).

de-Lys gneisses,[4] about 15,000 feet thick, are in probable fault contact with the Baie Verte formation, about 10,000 feet in thickness, which consists predominantly of greenstone of the greenschist facies of metamorphism. Minor amounts of graywacke, tuff, agglomerate, lava, slate, ferruginous chert, sandstone, and marble were recognized in the formation. The Mings Bight formation is a thickness of about 2,000 feet of gneisses and schists which occur in the eastern portion of the area.

The Baie Verte formation has been intruded by large, dominantly concordant bodies of ultramafic rock and gabbro. Much of the ultramafic rock has undergone intense serpentinization and steatitization. The gabbro has suffered saussuritization, uralitization, silicification, carbonatization, and alteration to zoisite-quartz and zoisite-prehnite rock.[5] Granite, quartz-porphyry, and quartz-diorite intrusions occur in the Baie Verte formation. Adjacent to the latter the greenstone and gabbro have been metamorphosed to the amphibolite facies. Small sills and dikes of mafic gabbro, porphyrite, diorite, and kersantite were observed in the area.

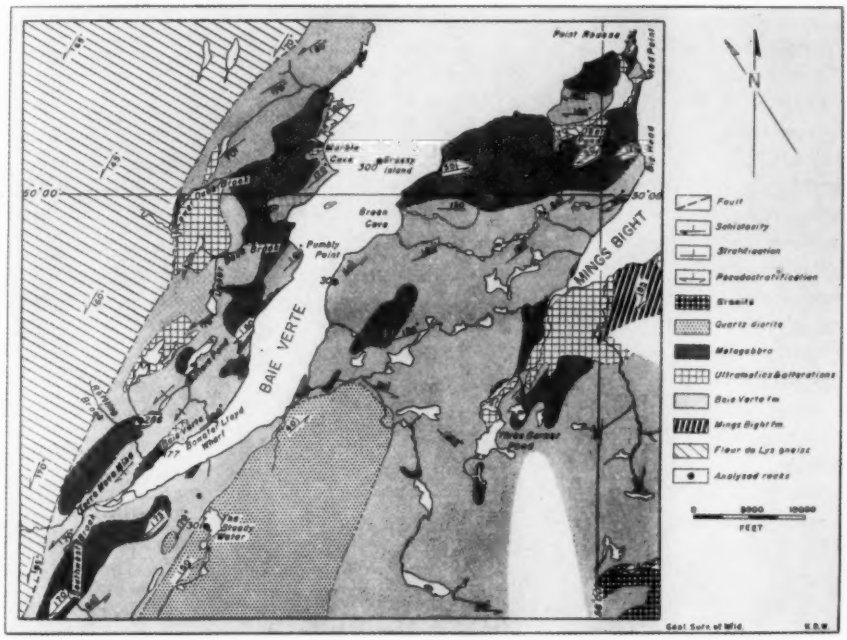

FIG. 2.—Geological map of the Baie Verte area

BAIE VERTE FORMATION

GREENSTONE

More than 90 per cent of the Baie Verte formation is composed of brownish-

[4] J. O. Fuller, "Geology and Mineral Deposits of the Fleur-de-Lys Area," *Newfoundland Geol. Surv. Bull.*, No. 15, 1941.

[5] Watson, "Zoisite-Prehnite Alteration of Gabbro," *Amer. Min.*, Vol. XXVII (1942), pp. 638–45.

weathering greenstone which varies in degree of alteration from highly crenulate chlorite schist to clearly recognizable graywacke and lava. The latter includes porphyritic lava containing subhedral phenocrysts of augite, amygdular types with calcite, epidote, quartz, and chlorite-filled vesicles, and a small amount of variolitic rock. Pillow structure (Fig. 3, *A*) was observed in a few places in the upper part of the formation.

The middle part of the Baie Verte formation contains three principal zones of greenstone which are characterized by small lenses or thin lenticular beds of dominantly red, ferruginous chert consisting of an aggregate of extremely small interlocking quartz grains throughout which minute plates of hematite are disseminated. Concentrically banded discrete or coalescent spherules (Fig. 5, *A*) and radially disposed, silica-filled cracks which were observed in some of the chert are suggestive of colloidal origin. Edward Sampson[6] has proposed that in the Notre Dame Bay region to the southeast the intimate association of somewhat similar cherts with volcanic rocks is indicative of a genetic connection.

GREENSCHIST FACIES

A microscopic study of several thin sections of the greenstone occurring in localities free from the immediate influence of granitic intrusives reveals that chlorite, albite, epidote, and quartz in a foliated aggregate are present in almost all cases.

Chlorite (Optically +, Ng − Np = .01) which is present as irregular plates and shreds averaging about 0.1 millimeter in length, constitutes about 25 per cent of the majority of specimens. The content ranges from as high as 50 per cent down to zero. Although albite occurs as small subhedral laths 0.2–0.1 millimeter long in a few cases, it is generally present as irregular grains of very small size. The content of albite, which is more constant than that of chlorite, also averages about 25 per cent. Epidote, which composes about 20 per cent of the greenstone occurs as small anhedral grains or aggregates of grains 0.05–0.1 millimeter in diameter. Clinozoisite is associated with the epidote in a few sections. Quartz, occurring as minute irregular grains up to 0.1 millimeter in size, constitutes 10 to 15 per cent of most of the greenstone examined. Over half of the sections studied contain small shreds and imperfect elongate prisms of pale green, faintly pleochroic actinolite. The content of actinolite, in those greenstones which contain it, varies from 10 to 35 per cent. In rocks of high content, chlorite is either absent or present in very small amounts. On the other hand, all of the actinolite-free greenstones are calcite-bearing to some degree. Sericite is present in small amounts. Pyrite, magnetite, sphene, apatite, and rutile comprise the accessory minerals.

The presence in the greenstone of the critical constituents, chlorite sericite, albite, and epidote, places the rock in the greenschist metamorphic facies as defined by Pentti Eskola.[7] The prevalence of the following assemblages:

1. Actinolite-(chlorite)-albite-epidote-quartz
2. Chlorite-(actinolite)-albite-epidote-quartz
3. Chlorite-calcite-albite-epidote-quartz

in the greenschist facies of the Baie Verte formation is best explained by the assumption that part of the chlorite of the second and third assemblages has formed in the place of actinolite.[8] It is postu-

[6] "The Ferruginous Chert Formations of Notre Dame Bay, Newfoundland," *Jour. Geol.*, Vol. XXXI (1923), pp. 571–98.

[7] "The Mineral Facies of Rocks," *Norsk Geologisk Tidsskrift* (1920), pp. 154–55.

[8] Cf. Eskola, "The Mineral Development of Basic Rocks in the Karelian Formations," *Fennia 45*, No. 19 (1925), pp. 77–78; F. J. Turner, "Metamorphism of the Te Anau Series in the Region North-west of Lake Wakatipu," *Trans. Roy. Soc. N.Z.*, Vol. LXV (1935), pp. 345–47; C. E. Tilley, "The Status of Hornblende in Low Grade Metamorphic Zones of Green Schists," *Geol. Mag.* (1938), pp. 497–511.

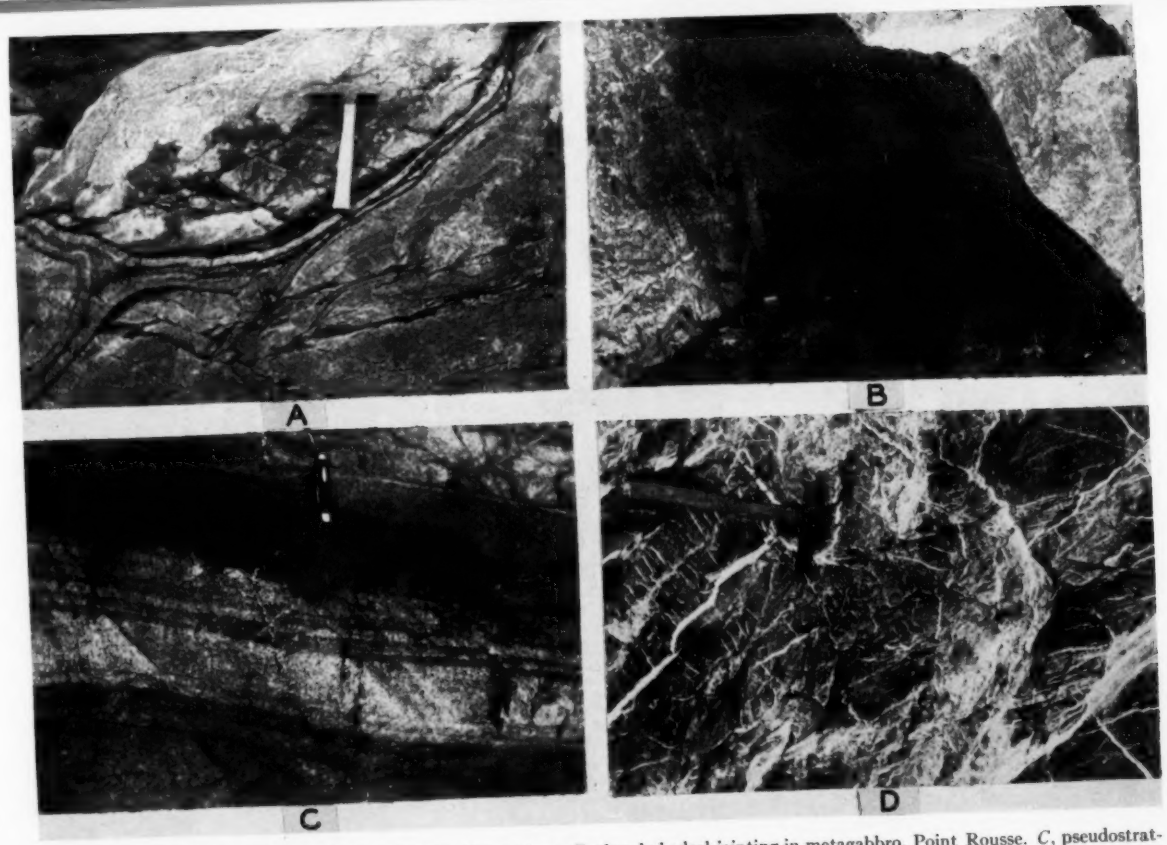

FIG. 3.—*A*, Pillow lava of Baie Verte formation, Green Cove. *B*, rhombohedral jointing in metagabbro, Point Rousse. *C*, pseudostratification in metagabbro. Note pegmatite veinlet near knife. Between Red Point and Big Head. *D*, cross-fiber and slip-fiber tremolite veinlets in mafic gabbro. South of Red Point.

lated that the formation takes place in the presence of solution sufficient to remove lime, in the second case, and in the presence of CO_2 to convert part or all the lime to calcite, in the third case.

The analysis of a specimen of greenstone from the southeast shore of Baie Verte, 2,500 feet south of Pumbly Point (Fig. 2), is given in Table 1. The average

TABLE 1

CHEMICAL ANALYSES OF GREENSTONE AND ALTERED PILLOW BASALTS

No. 30 Greenstone		Average Analysis of Five Altered Pillow Basalts†
Chemical Analysis*	Norm	
SiO_2 ..... 45.08	Qtz. 0.20	SiO_2 ..... 47.73
Al_2O_3 ..... 21.38	Or. 12.23	Al_2O_3 ..... 15.97
Fe_2O_3 ..... 3.82	Ab. ..... 12.58 } 49.54 Pc.	Fe_2O_3 ..... 2.55
	An. ..... 36.96 }	
FeO 5.52		FeO 7.64
MgO 6.62	En. ..... 16.60 } 21.83 Hy	MgO 6.80
CaO 7.95	Fs. ..... 5.23 }	CaO 10.11
Na_2O 1.52	Cor. 3.16	Na_2O 3.15
K_2O 2.14	Ilm. 1.82	K_2O 0.60
H_2O+ 4.68	Mt. 5.57	H_2O+ 2.58
H_2O- 0.05	Cal. 0.91	H_2O- 0.15
CO 0.40	H_2O+ 4.68	CO_2 ..... 1.05
TiO_2 ..... 0.99	H_2O- 0.05	TiO_2 ..... 1.29
		P_2O_5 ..... 0.14
	Pc = $Ab_{15}An_{85}$	S 0.01
	Or : Pc = 24.4 : 75.6	MnO 0.14
Total ..100.15	Total ..99.98	Total ...99.91

* Analysis by G. Kahan. Southeast shore of Baie Verte, 2,500 feet south of Pumbly Point (Fig. 2).

† G. R. Heyl, "Geology and Mineral Deposits of Bay of Exploits Area," *Newfoundland Dept. Nat. Res. Geol. Sect. Bull. No. 3* (1937), p. 21. (Analyses A & B, Fig. 1); G. H. Espenshade, "Geology and Mineral Deposits of the Pilleys Island Area," *Newfoundland Dept. Nat. Res. Geol. Sect. Bull. No. 6* (1937), p. 23 (Analysis C, Fig. 1); H. J. MacLean, "Geology and Mineral Deposits of Little Bay Area" (unpublished Princeton Ph.D. thesis, 1940), p. 62 (Analyses D & E, Fig. 1).

analysis of five altered pillow basalts from the Ordovician section of the Notre Dame Bay region (Fig. 1), with which the Baie Verte formation is believed to correlate, is included for comparison. It is seen that the greenstone is much richer in Al_2O_3, K_2O, and H_2O and poorer in Na_2O and FeO than the average basalt.

Similar differences are apparent when the analysis is compared with the analyses of altered Keewatin pillow lavas and greenstones recently compiled by J. Satterly,[9] the average of nineteen spilitic greenstones published by N. Sundius,[10] and analyses of chlorite schists and greenstones given by Eileen M. Guppy[11] and Walter Larsson.[12] It is suggested that potash metasomatism may have affected the rock selected for analysis, although minute veinlets of potash feldspar and quartz were not apparent as they were along the shore farther south in the vicinity of the quartz-diorite.

AMPHIBOLITE FACIES

In the south-central part of the quadrangle, the Baie Verte formation is intruded by a mass of quartz-diorite which occupies an area of approximately 12 square miles within the boundaries of the region studied.

The quartz-diorite is a gray, medium-grained rock which is slightly gneissic in places.

Microscopic study reveals that the plagioclase is highly altered.

The most abundant feldspar is albite ($Ab_{93}An_7$, Np 1.530, Nm 1.534, Ng 1.540) which occurs as subhedral and anhedral grains averaging about 1.5 millimeters in diameter. Many of the grains exhibit excellent polysynthetic twinning. Sericite, epidote and a little clinozoisite occur in abundance throughout the albite. In most cases, the alteration has been more intense in the centers of the grains than on their margins. Orthoclase, microcline, and perthite were observed in small amounts. The latter occurs as small interstitial grains. Occasional grains of quartz show trains of

[9] "Pillow Lavas from the Dryden-Wabigoon Area, Kenora District, Ontario," *Univ. Toronto Studies, Geol. Ser. No. 46* (1941), pp. 133–34.

[10] "On the Spilitic Rocks," *Geol. Mag.*, Vol. LVII (1930), p. 9.

[11] "Chemical Analyses of Igneous Rocks, Metamorphic Rocks and Minerals," *Mem. Geol. Surv. Great Britain* (1931).

[12] "Chemical Analyses of Swedish Rocks," *Bull. Geol. Inst. Univ. Upsala*, Vol. XXIV (1933), pp. 47–196.

fluid inclusions. Biotite (X = light brown, Y & Z = dark brownish green) containing inclusions of zircon surrounded by dark halos, occurs as flakes about 0.3 millimeter in length. Some of the flakes are altered to chlorite at their terminations and along cleavage planes. Epidote, in addition to its occurrence within the albite, is present as fairly large anhedral grains disseminated throughout the rock. It is also common as small veinlets about 0.1 inch in thickness. The accessory minerals include sphene (some of which appears almost uniaxial), apatite, zircon, ilmenite, rutile, garnet, calcite and pyrite.

An analysis of a sample of quartz-diorite from the west side of The Steady Water, 1,500 feet southwest from the point at which the trail meets the head of the pond (Fig. 2), is given in Table 2.

TABLE 2

CHEMICAL AND MINERAL ANALYSIS OF QUARTZ-DIORITE

Chemical Analysis*	Norm	Mode
SiO_2 ..... 68.27	Qtz..... 22.26	Quartz... 22.8
Al_2O_3 ..... 15.73	Or..... 10.56	Potash Feldspar... 3.1
Fe_2O_3 .... 1.27	Ab..... 44.01 } 56.24 Pc.	Albite.... 58.1
	An..... 12.23 }	Sericite.. 1.0
		Epidote.. 3.7
FeO 1.92		Biotite... 11.0
MgO 1.91	En..... 4.80 } 6.52 Hy	Sphene... 0.2
CaO 2.44	Fs..... 1.72 }	Apatite.. 0.1
		Zircon... 0.02
Na_2O 5.24	Mt..... 1.86	
K_2O 1.76	Ilm..... 0.91	
H_2O+ 0.77	Cor..... 0.71	
H_2O- 0.04		
	H_2O+... 0.77	
CO_2 ..... 0.04	H_2O-... 0.04	
TiO_2 ..... 0.47		
P_2O_5 ..... 0.18	Pc = $Ab_{79}An_{21}$	Pc = $Ab_{93}An_7$
MnO 0.06	Or : Pc = 15.8 : 84.2	
Total.. 100.10	Total.. 99.87	Total. 100.02

* Analysis by G. Kahan. No. 301 West side of The Steady Water, 1,500 feet southwest from point at which trail meets head of pond (Fig. 2).

For a horizontal distance of at least 1,000 feet from the northwest boundary and 4,500 feet from the eastern boundary of the quartz-diorite the greenstones have been raised in degree of metamorphism to the amphibolite facies. They consist of brown-weathering, dark green, fine to medium-grained, schistose rocks in which amphibole, feldspar, and biotite are megascopically visible in most cases.

Hornblende, which is characterized by a distinct pleochroism (X = pale yellowish green, Y & Z = dark green), occurs as subhedral prisms and shreds ranging from 0.25 to 0.5 millimeter in length, in most thin sections. The average hornblende content of the rocks of this facies is 40 to 50 per cent. In some specimens, oligoclase, and in others, plagioclase near the albite-oligoclase boundary, are present as small anhedral grains throughout the schist. It has been estimated that plagioclase constitutes from 15 to 20 per cent of the typical assemblage. Markedly pleochroic brown biotite (X = pale yellow, Y & Z = dark brown) is present as flakes about 0.1 millimeter in length which generally comprise 5 to 10 per cent of the section. The remaining major constituent is quartz and in most cases, epidote and clinozoisite. The epidote content of the amphibolite facies is noticeably less than that of the lower grade of metamorphism. Rutile and a black metallic were observed as accessories. Of these, rutile is the more abundant mineral, occurring in high concentration in proximity to the northern contact of the quartz-diorite mass. In one thin section, minute anhedral grains or aggregates of such grains, up to 0.25 millimeter in diameter constitute almost 5 per cent of the rock.

ULTRAMAFIC ROCKS

Bodies of ultramafic rocks and their alteration products are abundant in the area which was studied (Fig. 2). They occur principally in the Baie Verte formation as dominantly concordant intrusives of various sizes. The largest ultramafic mass extends from the bottom of Mings Bight to Three Corner Pond situated about 3 miles to the southwest, and outcrops over a maximum width of almost $1\frac{1}{2}$ miles.

PERIDOTITE AND SERPENTINIZED DERIVATIVES

Recognizable peridotite constitutes the greater part of two large intrusives in the Baie Verte formation, one of which occurs west of Butlers Pond and the other principally between Upper and

Lower Duck Brooks. A similar type of rock composes Grassy Island.

The weathered surface of the peridotite is characterized by a distinctive reddish-brown color and by the presence of gray pyroxene and black chromite grains which stand out in marked relief. Indistinct pseudostratification with bands varying from a few inches up to several feet in thickness is apparent upon the weathered surface in a few places. A fresh surface of the rock shows dark grayish-green crystals of pyroxene averaging about 0.1 inch in diameter in an extremely fine-grained, dark-green to black serpentinized groundmass.

Microscopic study reveals that both harzburgite and lherzolite are represented in the peridotite masses.

The harzburgite consists of large anhedral to subhedral crystals of enstatite ($2V = 80°+$; $Ng = 1.6725 \pm .002$; 91.50 per cent En) in an aggregate of irregularity interlocking serpentinized olivine grains averaging about 2 millimeters in diameter. The crystals of enstatite contain a few minute exsolution lamellas of diopsidic pyroxene oriented parallel to 100, the optic plane.[13] The olivine grains are separated into rounded and polygonal areas by a reticulating network of serpentine veinlets. Some of the enstatite crystals are replaced by serpentine on their peripheries. Magnetite is disseminated throughout the serpentine as minute grains. Chromite is present as highly irregular grains which have an average diameter of approximately 0.75 millimeter. Many of the grains are tonguelike and contain olivine inclusions and definitely appear to have crystallized late (Fig. 5, *B*). The texture of the harzburgite is best described as "pseudo-porphyritic" inasmuch as the large crystals of enstatite which resemble phenocrysts, contain inclusions of olivine, indicating that they probably crystallized late.

An analysis of a sample of harzburgite from the eastern shore of Grassy Island, 350 feet from the northern end (Fig. 2), is given in Table 3. Rosiwal analysis indicates that the mineralogical composition of the rock prior to serpentinization was as follows: olivine, 88.6 per cent by weight; enstatite, 10.3 per cent by weight; chromite, 1.1 per cent by weight. The olivine and enstatite are now serpentinized to the extent of approximately 50 per cent and 20 per cent, respectively.

TABLE 3

CHEMICAL ANALYSES OF SERPENTINIZED HARZBURGITE

	No. 300*	Bay of Islands†
SiO_2	39.39	39.26
Al_2O_3	0.98	1.82
Fe_2O_3	3.00	4.27
FeO	4.97	3.02
MgO	41.93	38.53
CaO	0.50	1.25
Na_2O	0.06	0.23
K_2O	None	None
H_2O+	8.43	10.05
H_2O-	0.21	0.58
CO_2	0.11	0.47
TiO_2	0.01	0.04
P_2O_5	Trace	.....
Cr_2O_3	0.27	0.39
MnO	0.12	0.11
Total	99.98	100.02
Mg:Fe (molecular ratio)	9.98	10.05

* Analysis by G. Kahan. Eastern Shore of Grassy Island, 350 feet from northern end (Fig. 2).

† J. R. Cooper, "Geology of Southern Half of the Bay of Islands Igneous Complex," *Newfoundland Dept. Nat. Res., Geol. Sect. Bull. No. 4*, 1936), Appen. 1.

An analysis of serpentinized harzburgite from the Bay of Islands igneous complex (Fig. 1) is included in Table 3 for comparison. The molecular ratio of Mg to Fe in the Baie Verte and Bay of Islands rocks is 9.98 and 10.05, respectively. It is interesting to note that Hess[14] has found that the Mg/Fe ratios

[13] H. H. Hess, and A. H. Phillips, "Optical Properties and Chemical Composition of Magnesian Orthopyroxenes," *Amer. Min.*, Vol. XXV (1940), pp. 271–85.

[14] "A Primary Peridotite Magma," *Amer. Jour. Sci.*, Vol. XXXV (1938), pp. 341–43.

of the rocks which he believes represent the primary ultramafic magma series are greater than 7.5 and in many examples are between 9 and 10.

The lherzolite contains crystals of clinopyroxene in addition to olivine, enstatite, chromite, serpentine, and magnetite.

The clinopyroxene is diopside with an optic angle of approximately 60°, a birefringence of .024+ and an extinction angle of 35° to 40°. It occurs as anhedral grains averaging about 1.0 millimeter in diameter. A highly serpentinized lherzolite from the western shore of Grassy Island was estimated to contain about 15 per cent enstatite and 10 per cent clinopyroxene.

Serpentinized peridotite masses, indicated to be sill-like by a magnetic survey, crop out in the vicinity of the Terra Nova mine. The rock contains serpentinized clinopyroxene, chromite and abundant serpentine and magnetite derived from olivine.

An interesting type occurring on Southwest Brook about a mile from the mine consists of a serpentine groundmass containing large irregular crystals of diopside with numerous poikilitic inclusions of serpentine and magnetite after olivine. Although the inclusions have a well-defined relict rounded outline (Fig. 5, *C*), they appear to have been partially replaced by the pyroxene with the result that their actual form is extremely irregular (Fig. 5, *D*).

Serpentinized peridotite consisting principally of pyroxene occurs in a few localities in the area. In a mass of serpentine behind the settlement of Baie Verte, there are unsheared portions which consist almost entirely of pseudomorphs of pyroxene crystals $\frac{1}{4}$ inch in length.

Pyroxene-rich peridotite which has suffered only partial serpentinization was observed as small bodies on Upper Duck Brook and east of Deer Pond.

The pyroxene (diopside; $2V = 60° \pm$) which constitutes over 75 per cent of the rock, is present as anhedral grains about 1.5 millimeters in diameter, separated by interstitial serpentine. Tremolite has resulted from the alteration of the pyroxene in some cases.

SERPENTINE

The peridotite of many localities in the region is so completely serpentinized that no unaltered pyroxene or olivine remain. However, in several cases, relict textures clearly show the original character of the rock. Rounded areas of serpentine containing magnetite concentrated along lines arranged in an irregular fracture-like pattern, represent altered olivine, and bastite is indicative of the original presence of pyroxene.

In many places the serpentine is highly sheared with the result that the relict textures have been obliterated. Typical sheared serpentine consists of a matlike aggregate of serpentine shreds and flakes throughout which minute grains of magnetite and chromite are disseminated.

TALC-CARBONATE

Alterations of the ultramafic rocks to assemblages consisting principally of pale-green talc and buff-colored carbonate, in various proportions, are of common occurrence.

The reddish brown weathering carbonate (No = 1.695, Ne = 1.51) occurs as irregular grains which have an average diameter of about 1 millimeter but they attain a size of 1.5 inches in a few cases. The talc is present as an aggregate of minute fibers and shreds. Accessory minerals include magnetite, chromite, and specular hematite.

SERPENTINIZATION AND STEATITIZATION

The serpentinization of the ultramafic rocks is considered to be an autometamorphic reaction, because there is no apparent localization of the alteration to the margins of the bodies, and in the partially serpentinized peridotites the olivine relicts are approximately uniformly spaced and exhibit the same degree of

replacement.[15] The alteration of the serpentinized ultramafics to talc-carbonate rock is probably attributable to the presence of hydrothermal solutions which were related to the granitic intrusions of the area.[16]

AGE

The ultramafics intrude the Baie Verte formation which corresponds lithologically to the Ordovician of Notre Dame Bay. The occurrence in some of the ultramafic bodies of steeply dipping pseudostratification, approximately parallel to the foliation of the greenstones, suggests that their intrusion preceded the major folding.[17]

Pseudostratified sheets of ultramafic rocks occurring in the Ordovician of Betts Cove-Tilt Cove, Trout River, Bay of Islands and Hare Bay areas (Fig. 1, *1*, *2*, *3*, and *4*) have been described by A. K. Snelgrove[18] and Earl Ingerson[19] and J. R. Cooper,[20] respectively. Those in the west coast region are of pre-Mississippian age and are considered by Ingerson to have been intruded during the Devonian, and by Cooper, near the close of the Ordovician.

Ultramafic rocks occur in relative proximity to Newfoundland in the southwestern continuation of the Appalachian mountain system in Gaspé and southeastern Quebec. In Gaspé the ultramafics intrude metamorphosed Ordovician volcanics which are overlain unconformably by less highly metamorphosed Silurian and Devonian rocks. No ultramafics occur in the post-Ordovician rocks and, therefore, they are considered by F. J. Alcock[21] to have been intruded at the close of the Ordovician.

A similar conclusion regarding the age of the peridotite in the Thetford area of southeastern Quebec has been reached by H. C. Cooke.[22] In this region the intrusions have been controlled by post-Ordovician folding and have been folded by post-Lower Devonian movement.

Lacking any definite data on the age of ultramafic intrusives of Newfoundland, the writer suggests that they may be Taconic by correlation with the petrographically similar rocks which occur in the adjacent portion of the Appalachians.

METAGABBRO

The majority of the numerous metagabbro bodies which intrude the rocks of the Baie Verte formation are dominantly concordant, although locally they transect the foliation of the country rock.

The metagabbro is composed principally of saussuritized plagioclase and uralitized pyroxene in varying proportions. For the most part, it is a light greenish-gray, medium-grained massive rock exhibiting well-developed rhombohedral jointing (Fig. 3, *B*), although local phases are highly sheared and therefore

[15] Hess, "The Problem of Serpentinization and the Origin of Certain Chrysotile Asbestos, Talc and Soapstone Deposits," *Econ. Geol.*, Vol. XXVIII (1933), pp. 652–53.

[16] *Ibid.*, p. 635.

[17] Joe Webb Peoples, "Gravity Stratification as a Criterion in the Interpretation of the Structure of the Stillwater Complex," *Montana Rept., 16th Internat. Geol. Cong.* (1933), pp. 353–60.

[18] "Geology and Ore Deposits of Betts Cove-Tilt Cove Area, Notre Dame Bay, Newfoundland," *Can. Inst. Min. Met. Monthly Bull. 228* (1931), pp. 477–519.

[19] "Layered Peridotitic Laccoliths of the Trout River Area, Newfoundland," *Amer. Jour. Sci.*, Vol. XXIX (5th ser., 1935), pp. 422–40.

[20] "Geology of Southern Half of the Bay of Islands Igneous Complex," *Newfoundland Dept. Nat. Res., Geol. Sect. Bull. No. 4* (1936); "Geology and Mineral Deposits of the Hare Bay Area," *ibid.*, No. 9 (1937).

[21] "Geology of Chaleur Bay Region," *Geol. Surv. Canada Mem. 183* (1935), p. 38.

[22] "Thetford Disraeli, and Eastern Half of Warwick Map Areas, Quebec," *Geol. Surv. Canada Mem. 211* (1937), pp. 70–71.

difficult to distinguish from the greenstone of the area.

None of the thin sections which were examined showed unaltered plagioclase, and a relatively small proportion of them contained any unaltered pyroxene. A study of fresh-appearing specimens from the intrusive to the northwest of the Terra Nova Mine, revealed that the pyroxene, occurring as anhedral grains averaging about 0.25 millimeter in diameter is augite[23] ($2V = 47.5°$; $Np = 1.690$; $Ng = 1.718 \pm .003$). Many of the grains are twinned. Most of the augite shows an irregular peripheral alteration to actinolite or colorless tremolite. Some, however, is altered to actinolitic hornblende characterized by a fairly deep color and distinctive pleochroism. Plagioclase occurs as irregular polysynthetically twinned laths, 0.75 millimeter in average length, which are highly altered. They consist of albite throughout which numerous small prisms of clinozoisite and grains of epidote are disseminated. Clinozoisite also occurs as clusters of euhedral prisms in areas interstitial to the plagioclase laths. Leucoxene is present in abundance as pseudomorphs of subhedral skeletal crystals of ilmenite about 0.3 millimeter in diameter.

The chemical analysis and mode of a specimen of massive rock consisting of saussuritized plagioclase and partially uralitized augite from the southwest shore of Baie Verte, 2,300 feet south of the Bowater Lloyd Company's wharf (Fig. 2), is given in Table 4.

PEGMATITE FACIES

In many places small, irregular masses of metagabbro with pegmatitic texture occur throughout the intrusives. Sharply defined contacts with the rock of normal texture are rarely observed (Fig. 4, *A*). The pegmatite consists of large crystals of saussuritized plagioclase and partially or completely uralitized pyroxene, which attain a length of several inches in some places. Within the pegmatite bodies there are commonly striking variations in the mineral proportions.

PSEUDOSTRATIFICATION

Well-defined pseudostratification was observed in several thick horizons of the large sills in the vicinity of Point Rousse (Fig. 3, *C*). In some cases the bands, which range from 0.1 inch to a foot in thickness, continue with regularity for 50 or 100 feet along the strike before they terminate by lensing out or are faulted off by movement along transverse joint planes. Their attitude is approximately conformable to the basal contacts of the sills. The tabular and prismatic crystals are oriented with their major axes paral-

TABLE 4*

Metagabbro No. 177†			Zoisite-Prehnite No. 286‡
Chemical Analysis	Norm		Chemical Analysis
SiO_2 ..... 48.74	Or..... 0.56	57.42 Pc. $Ab_{30}An_{70}$	SiO_2 ..... 44.15
Al_2O_3 ..... 18.26	Ab..... 15.72		Al_2O_3 ..... 19.07
Fe_2O_3 ..... 1.23	An..... 41.14		Fe_2O_3 ..... 1.03
FeO 4.08	En..... 8.90	24.18 Di.	FeO 2.49
MgO 8.76	Fs..... 2.64		MgO 5.37
CaO 14.40	Wo..... 12.64		CaO 25.22
Na_2O 1.87	En..... 5.43	6.97Hy.	Na_2O 0.14
K_2O 0.10	Fs..... 1.54		K_2O 0.00
H_2O+ 2.25	Fo..... 5.30	6.96 Ol.	H_2O+ 2.46
H_2O- 0.02	Fa..... 1.06		H_2O- 0.03
CO_2 ..... 0.05	Mt..... 1.86		CO_2 ..... 0.03
TiO_2 ..... 0.18	Ilm..... 0.30		TiO_2 ..... 0.14
P_2O_5 ..... 0.01	H_2O+ 2.25		P_2O_5 ..... 0.02
MnO 0.10	H_2O- 0.02		MnO 0.08
Total..100.05	Total..100.06		Total..100.23

Analyses by: G. Kahan.

	Metagabbro 177	Zoisite-Prehnite 286
Mode; percentage by weight	Altered plagioclase 53	Zoisite 83
	Pyroxene and alterations 47	Phrenite 15
		Actinolite 2
Specific gravity	3.01	3.18
Porosity; percentage	0.3	0.1

* Watson, "Zoisite-Phrenite . . . . ," *op. cit.*

† Southwest shore of Baie Verte, 2,300 feet south of the Bowater Lloyd Company's wharf (Fig. 2).

‡ South bank of Rattling Brook, 4,600 feet N. 15° W. from its mouth (Fig. 2).

[23] Hess, "Pyroxenes of Common Mafic Magmas," *Amer. Min.*, Vol. XXVI (1941), p. 520.

lel to the plane of the foliation, but they show no linear arrangement within the plane. The contacts between adjacent bands are relatively sharp in some cases and gradational in others. Within many of the bands there is a variation from a pyroxene-rich facies at the bottom to a feldspar-rich one at the top (Fig. 4, *B*). This density gradation proved to be an interesting criterion for checking the determination of the tops of the sills, although in several cases indeterminate relationships and reversals were noted.

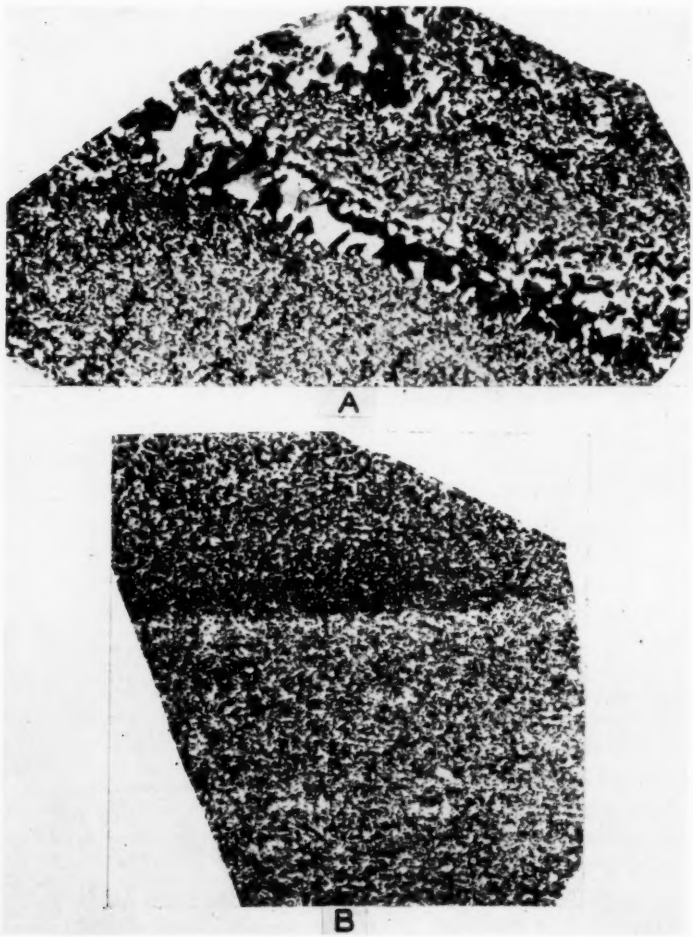

FIG. 4.—*A*, pegmatite in metagabbro of normal texture. Note gradational contact in places. Natural size. *B*, density gradations in pseudostratified metagabbro. Top is up. Natural size.

Hess[24] has concluded that the factors responsible for primary banding in gabbro are: (1) the relative density differ-

[24] "Primary Banding in Norite and Gabbro," *Trans. Amer. Geophys. Union* (1938), p. 266.

ences between each of the main constituents settling, plagioclase and pyroxene, compared to the density of the magma; (2) disturbance of the normal state of tulating that they were intruded in an approximately horizontal position and were crystallizing during the period of folding.

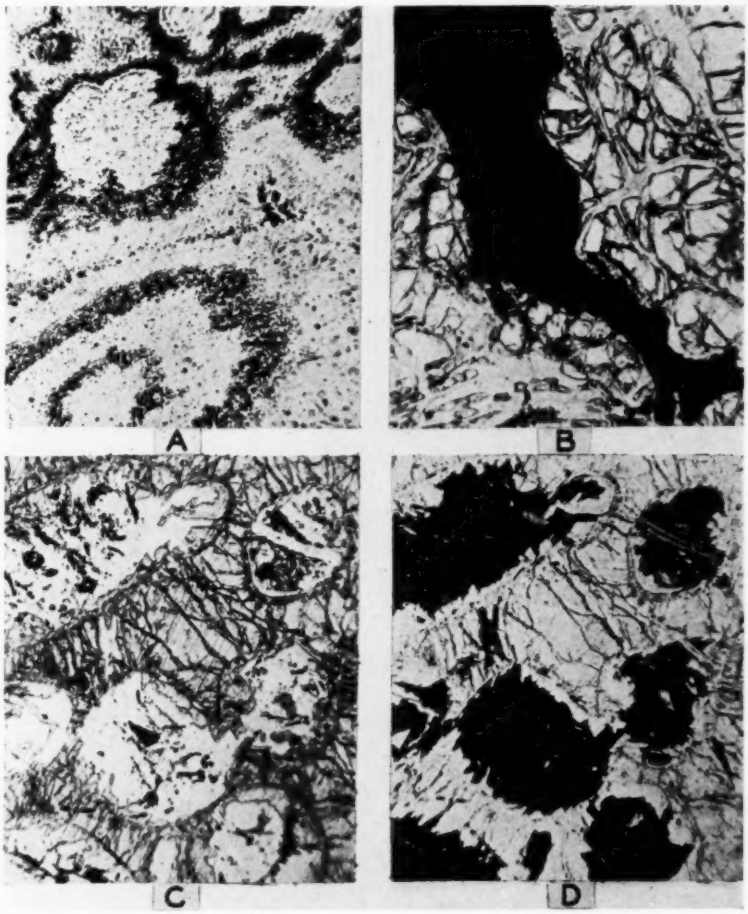

FIG. 5.—*A*, photomicrograph of colloform structure in ferruginous chert. Cluster and string of subhedral pyrite grains near center. Magnification: ×27. *B*, late chromite grain in serpentinized olivine. Magnification: ×40. *C*, relict rounded outlines of olivine grains included in and partially replaced by diopside, and subsequently serpentinized. Magnification: ×40. *D*, same field as *C* with crossed nicols. Note replacement of inclusions by diopside. Magnification: ×40.

quiescence in the magma by short epochs of gentle flow.

This explanation may be applied to the pseudostratification observed in some of the sills of the Baie Verte area by pos-

AMPHIBOLITE FACIES

Metagabbro occurring within the contact aureole of the quartz-diorite has also been converted to the amphibolite facies. This rock, which differs from the meta-

morphosed greenstone in being coarser grained and more massive, contains hornblende, oligoclase, biotite, epidote, zoisite, quartz, and chlorite. The accessory minerals include abundant rutile and small amounts of ilmenite, leucoxene, magnetite, and apatite.

ZOISITE-QUARTZ AND ZOISITE-PREHNITE ALTERATIONS

In the area between Lower Duck Brook and Marble Cove, much of the gabbro has been altered to a white, medium- to fine-grained, schistose rock composed of zoisite and quartz. The quartz occurs in the interstices between anhedral zoisite grains or aggregates of grains and as small veinlets. Adjacent to serpentine the rock contains abundant minute flakes of bright green fuchsite.[25]

Near the northern end of the metagabbro body which terminates a short distance north of Rattling Brook, the rock has been altered to an aggregate consisting principally of zoisite and prehnite.[25] The zoisite-prehnite rock varies from very fine to fairly coarse grained and is white or faintly greenish due to the presence of actinolite. Although outcrops are not abundant, it appears that the alteration extends over an area of several hundred square feet and grades into the normal metagabbro. Microscopically it is seen that the zoisite is intricately traversed by a network of minute prehnite veinlets.

The analysis of zoisite-prehnite rock from the south bank of Rattling Brook at a point 4,600 feet N. 15° W. from its mouth (Fig. 2) is given in Table 4. A comparison of its composition with that of the typical metagabbro shows that the principal change involved in its formation was the addition of lime. Decrease in the silica, iron, magnesium, and alkali content is also noticeable. It is suggested that the zoisite-prehnite and zoisite-quartz alterations have resulted from the action of hydrothermal solutions probably related to the granitic rocks of the area.

[25] Duncan Whitmore, "The Chromium Micas." Unpublished report of the National Research Council of Canada, 1940.

[26] Watson, "Zoisite-Prehnite . . . . , *op. cit.*

OTHER ALTERATIONS

Silicification and carbonatization, alone or in combination, have affected the metagabbro of several localities.

Fibrous tremolite was observed in abundance as narrow slip-fiber and cross-fiber veinlets in the metagabbro in a few places, particularly in the highly mafic portions (Fig. 3, *D*).

AGE

The metagabbro is younger than the rocks of the Baie Verte formation, since it exhibits chilled contacts against them in several places and is older than the quartz-diorite, since the latter has metamorphosed it to the amphibolite facies within the contact aureole. Well-exposed, unsheared contacts between the metagabbro and ultramafics were not observed and, in the few places where they are exposed in proximity, no critical data were obtainable.

MINOR INTRUSIVES

MAFIC GABBRO

Dark gray, medium- to fine-grained, massive dikes of mafic gabbro occur in abundance within the larger metagabbro bodies of the area. The dikes are from less than a foot up to 25 feet wide. Individually they show striking uniformity in width and have marked chilled contacts. In most cases their intrusion appears to have been controlled by the joint pattern of the country rock.

Augite which occurs as small, irregular, twinned and untwinned grains averaging about

0.2 millimeter in diameter, composes about 40 per cent of the rock. Hornblende (X = light, yellowish brown, Y & Z = dark greenish brown) is present as separate prisms and as replacements on the margins of the augite crystals. Highly saussuritized, polysynthetically twinned, irregular laths of plagioclase, averaging 0.5 millimeter in length, are also a major constituent. Leucoxene replacing large skeletal crystals of ilmenite is abundant. Zoisite, quartz, and apatite were observed in small amounts.

DIORITE

Several narrow, nonporphyritic, medium- to fine-grained sills of intermediate composition were observed in the greenstones in the vicinity of Baie Verte settlement. They show well-defined chilled contacts and are readily distinguishable from the adjacent greenstones because of their massive character.

Hornblende (X = light yellowish green, Y & Z = dark green) occurring as irregular prisms 0.5 to 1.0 millimeter in length, is an important constituent of the rock. Partial alteration of the hornblende to actinolite and chlorite has taken place. Cloudy grains of albite also occur in abundance in the sills. Epidote is present as small grains within the albite and also as crystals about 0.2 millimeter in diameter, throughout the remainder of the rock. Skeletal crystals of leucoxene, commonly containing relict ilmenite, were observed in abundance in some of the thin sections examined.

PORPHYRITE

Massive porphyritic sills, a few feet in thickness, exhibiting chilled margins, occur in the greenstones of the area in several places. The rock contains highly saussuritized plagioclase laths averaging about 4 millimeters in length and showing a slight alignment. They occur in a fine-grained, greenish-gray groundmass which contains abundant actinolite.

LAMPROPHYRE (KERSANTITE)

A steeply-dipping kersantite dike, 15 feet in width, was observed transecting rocks of the Baie Verte formation in the channel of Upper Duck Brook. The kersantite is a medium-grained, panidiomorphic textured, massive, dark gray rock in which brown biotite, hornblende, and feldspar are megascopically visible.

Biotite (X = pale yellow, Y & Z = tan) occurs as flakes 0.3–0.5 millimeter in length. Hornblende (X = light yellowish brown, Y & Z = dark brown) is present as subhedral prisms of about the same length, many of which have irregular coronas of tremolite. Augite was observed as anhedral grains 0.3 millimeter in diameter, which have been partly replaced by actinolite and chlorite in many cases. Albite occurs as subhedral and anhedral crystals averaging about 0.5 millimeter in length. Slender prisms and needles of apatite up to 0.5 millimeter in length were observed in abundance. The remaining minerals of the kersantite are carbonate, ilmenite and leucoxene.

SUMMARY AND CONCLUSIONS

Greenstone of the Baie Verte formation consists predominantly of one of the following assemblages:

1. Actinolite-(chlorite)-albite-epidote-quartz
2. Chlorite-(actinolite)-albite-epidote-quartz
3. Chlorite-calcite-albite-epidote-quartz

It is believed that part of the chlorite of 2 and 3 has developed in place of actinolite in the presence of solutions capable of removing lime, in the second case, and in the presence of CO_2 to fix part or all of the lime in calcite, in the third case.

Adjacent to a large quartz-diorite intrusive, greenstone, normally containing the critical constituents, chlorite, sericite, albite, and epidote of the greenschist facies, has been converted to the amphibolite facies characterized by hornblende, oligoclase, and biotite.

Some of the chert lenses associated with the greenstones show concentrically

banded spherules which are suggestive of colloidal origin.

The molecular ratio of Mg/Fe in the serpentinized harzburgite is 9.98, which is within the range typical of the primary ultramafic magma series of Hess. The serpentinization which has affected the ultramafics is considered to be deuteric, but the steatitization is regarded as a later hydrothermal effect.

It is suggested that the pseudostratification observed in some of the metagabbro sills may have resulted from disturbance of the normal delicate differential settling of plagioclase and pyroxene crystals caused by folding during crystallization.

The alteration of the metagabbro to zoisite-quartz and zoisite-prehnite assemblages is believed to be an effect of hydrothermal solutions related to the granitic rocks of the area.

The Baie Verte formation is lithologically similar in several respects to parts of the Ordovician section of Notre Dame Bay. It is suggested that the ultramafics may be Taconic because of the occurrence of similar ultramafics of probable Taconic age in Gaspé and southeastern Quebec. No well-exposed, unsheared contacts between the ultramafics and metagabbro were observed. The metagabbro is definitely older than the quartz-diorite, since it has been metamorphosed to the amphibolite facies within the contact aureole.

ACKNOWLEDGMENTS.—The field work upon which this paper is based was carried out while the writer was investigating the cupriferous pyrite and gold deposits of the area[27] for the Geological Survey of Newfoundland during the summers of 1938 and 1939. A large portion of the laboratory expenses was borne by the Department of Geology of Princeton University.

The writer wishes to thank Professor A. K. Snelgrove for advice in the field, Professor H. H. Hess for assistance in the optical work, and Professor A. F. Buddington for considerable help during the preparation of the manuscript.

[27] G. Vibert Douglas *et al.*, "Copper Deposits of Newfoundland," *Newfoundland Geol. Surv. Bull. No. 20* (1940), pp. 13–23, 66–67, 83–86.

GLACIATION OF THE DU NOIR VALLEY FREMONT COUNTY, WYOMING

NEIL A. MINER
Cornell College

DAVID M. DELO
Knox College

ABSTRACT

Two stages of glaciation are recognized in the Du Noir River Valley. The first of these, previously recognized, is believed to be early Wisconsin, probably Iowan, in age and probably is to be compared with the Wisconsin I glaciation described by L. L. Ray in the southern Rocky Mountains. A second glacial stage, hitherto unrecognized, is believed to represent a late stage of the Wisconsin glaciation, probably comparable to the Wisconsin II stage as described by Ray.

INTRODUCTION

The Du Noir Valley is located fifteen miles northwest of Dubois, Fremont County, Wyoming, near the northwestern end of the Wind River Basin. Several southward-flowing headwater streams rising high against the Continental Divide at the southern edge of the Absaroka Plateau combine to form the Du Noir River, which flows in a south-southeasterly direction for 9 miles before joining the Wind River. The total drainage area of the Du Noir Valley system is approximately 100 square miles, of which about two-thirds lies to the northward of the junction of the tributary headwater streams. This upper drainage basin is bounded by cliffs of stratified volcanic rocks of the plateau, 300–600 feet high, which rise to elevations approximating 11,000 feet. During the Pleistocene this entire area formed a catchment basin for an ice mass which moved southward through the lower valley, and one small glacier still exists on the eastern slope of Du Noir Mountain.

Although reconnaissance observations have been made in this region at intervals since the early Hayden surveys, no detailed work has been published on this area. In connection with their work with the Cornell-Knox Summer Geology School, the writers have spent parts of two field seasons in the region, giving particular attention to the lower valley of the Du Noir River, which appears to be the critical area for interpreting the geologic history and structure of the upper end of the Wind River Basin. Detailed conclusions concerning the structure have not as yet been completed, but the major phases of the glacial history of this interesting area seem to have been deciphered.

UPPER DU NOIR VALLEY

The source of Du Noir River consists of two main forks—West Fork and East Fork (Fig. 1, *1*). Both streams head in cirques. Postglacial stream erosion has developed canyons, or deepened earlier ones, to a depth of 200 feet in the lower portions of both valleys. Between 3 and 6 miles below the junction of East and West forks three tributary streams enter the main valley from the east. From north to south these are Sixmile, Fivemile, and Fourmile creeks. From each of these valleys a mass of glaciofluvial material has been carried far out into

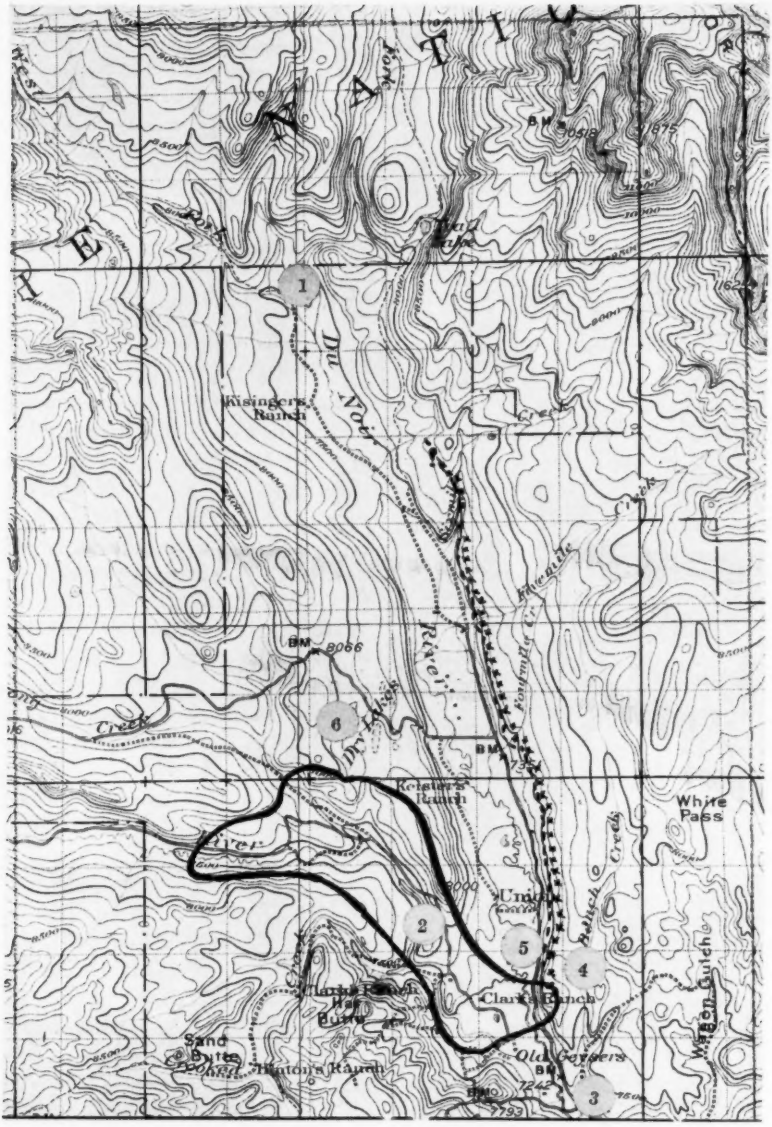

FIG. 1.—Map of the Du Noir River area showing Bull Lake lateral moraine (xxxxxxxxxx) and Pinedale lateral moraine (.....). Enclosed area represents the terminal moraine of combined Du Noir, Wind River, and Long Creek glaciers. All numerals refer to text. Scale 1:125,000. Contour interval 100′. U.S.G.S. topographic map.

Du Noir Valley and deposited as a large alluvial fan which has forced the Du Noir River to the western side of its valley.

LOWER DU NOIR VALLEY

The lower portion of the Du Noir Valley, with which this paper deals mainly, is a broad, flat-floored depression which joins the narrower valley of the Wind River obliquely, about 10 miles above Dubois (Fig. 2, *1*). The average width of the valley is about three-fourths of a mile, but at the juncture with the Wind River Valley this is increased to 2 miles as measured parallel to the axis of the latter. The western wall of the Du Noir Valley is straight and terminates at the south end in a narrow projecting spur which rises about 600 feet above the valley floor (Fig. 1, *2*). The spur curves westward and upstream into Wind River Valley, attesting the superiority of the Du Noir ice lobe (Fig. 2, *2*).

At this point the floor of the Wind River Valley (Fig. 2, *3*) is between 200 and 300 feet higher than the Du Noir River (Fig. 2, *4*) and consists of morainic debris. Just below the junction of the two rivers, the Wind River Valley narrows conspicuously, and the stream flows through a short narrow gorge walled by steeply dipping Tensleep sandstone. Two prominent alluvial benches, the lower about 50 feet and the upper at least 100 feet above the river, lie on the northern edge of this gorge and are capped with coarse stream gravels (Fig. 1, *3*).

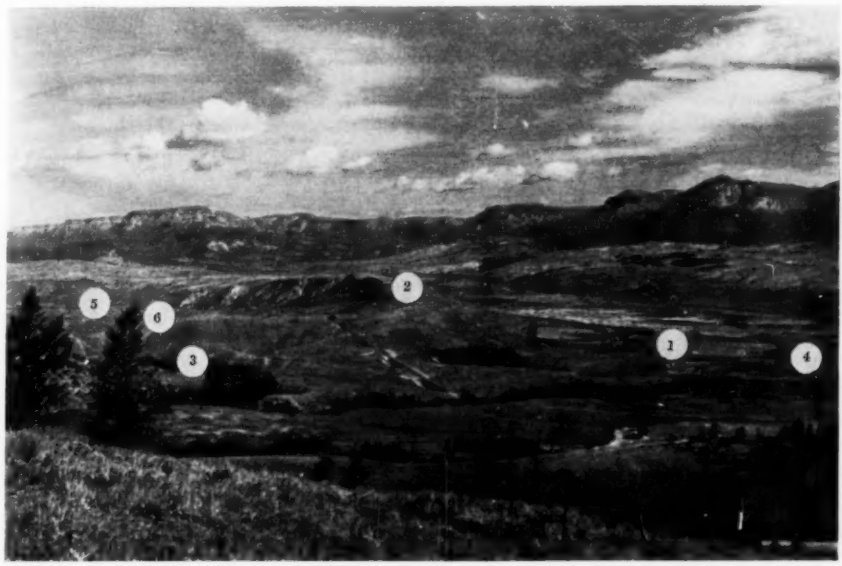

FIG. 2.—View northeast at the junction of Du Noir and Wind River valleys. The Owl Creek Range appears in the background. Numerals refer to the text.

BULL LAKE MORAINE

A lateral moraine extends from this narrow part of the Wind River Valley

in the vicinity of Bench Creek (Fig. 1, *4*), northward along the eastern side of the valley and continues up the Du Noir Valley. It lies approximately 300 feet above the floor of the valley and extends almost unbroken to Fourmile Creek (Fig. 3, *1*). The crest of the moraine descends along the valley 25 feet per mile. The moraine has a relief of approximately 50 feet and apparently rests upon

FIG. 3.—Northwest along the crest of the Bull Lake moraine. Ramshorn Peak in the right background.

a bench or surface of the Circle erosion level of Eliot Blackwelder.[1] Numerous Madison limestone and Tensleep sandstone boulders are strewn over its surface, but the dominant boulders are volcanics. Blackwelder noted this moraine in 1915 and identified it as Bull Lake. He states.

> At the mouth of the Du Noir River near the west end of the Wind River Basin, the position of the old terminal moraine is occupied by a spacious river floodplain; nevertheless, the old lateral moraine, now 200–300 feet above the river, is still largely intact and can be readily identified by its hummocky topography.[2]

Boulders on the surface are not so numerous as on the younger moraine in this same valley. The surprising feature is the apparent freshness of the limestone boulders. They do not appear so deeply weathered as one would expect if, as postulated by Blackwelder, the moraines are of Illinoian age. The limestones are weathered to a depth of about $\frac{1}{8}$–$\frac{1}{4}$ inch. For this reason the writers suggest a younger age than that ascribed by Blackwelder.

[1] "Post Cretaceous History of Western Wyoming," *Jour. Geol.*, Vol. XXIII (1915), p. 325.

[2] *Ibid.*, p. 327.

PINEDALE MORAINE

A second lateral moraine lies downslope from the "Bull Lake" moraine (Fig. 1, *5*). This lower moraine is identified by the writers as representing the Pinedale stage of glaciation. The two moraines are separate as far north as Sixmile Creek; there they come together and above that point their individual identity is lost. Where crossed by the road to the Wyoming Tie and Timber Company, a short distance south of Sixmile Creek, the Pinedale moraine appears about 75 feet downslope from the Bull Lake. Continuing south in Du Noir Valley, this distance increases progressively and the moraine slopes at about 35 feet per mile. The Pinedale moraine is not so large as the Bull Lake. Maximum relief is not over 40 feet and the average is about 30 feet. The general appearance of the weathered boulders is strikingly similar to those encountered on the Bull Lake moraine. Surficially, the limestone boulders of the two moraines show little difference, but weathering has penetrated not more than $\frac{1}{8}$ inch from the surface. Madison limestone boulders are more abundant, however, and there is a noticeable increase in the number of Tensleep boulders. This is probably due to the stratigraphic position of the Madison formation, the earlier valleys not penetrating the Madison very deeply. The continuity of the Bull Lake moraine is locally broken at the entrance of Fourmile and Fivemile creeks,

but the Pinedale remains undisturbed except for a slight bowing at the mouths of these valleys.

The lower Pinedale moraine being undisturbed while the higher one is definitely breached indicates that the lower moraine is later than the upper. The slight difference in depth of weathering and the similarity of the weathered appearance of boulders on the two moraines forcibly demonstrate the caution that must characterize the differentiation of glacial materials upon this basis in a semiarid region.

Blackwelder states, in discussing the Wind River Basin generally:

> In many canyons glacial drift of two distinct ages can be recognized easily, and it seems to me there is sufficient evidence that the later stage of glaciation is divisible into two quite distinct episodes. There are a few facts which hint at a still older or fourth stage, but they may be otherwise interpreted. Without attempting an actual correlation, the three sets of deposits may be compared to the late and early Wisconsin and the Illinoian or the Kansas drift sheets in the Mississippi Valley region.[3]

He further states, in discussing the Bull Lake stage in the Wind River Range and following a discussion of the Pinedale stage:

> The next older moraines, which I have compared with the early Wisconsin drift of Illinois, will be called the Bull Lake drift, from the locality of that name on the north slope of the Wind River Range. The deposits of this stage are definitely related to the terraces of the Circle erosion cycle in that they blend into the gravel strewn benches as modern moraines blend into their outwash deposits.[4]

L. L. Ray[5] concludes from his studies in the Medicine Bow Mountains of southern Wyoming that the glaciation in that area represents two substages of the Wisconsin—Wisconsin I and Wisconsin II. The Wisconsin I moraine would be correlated with the Iowan of the Middle West and Wisconsin II would represent Tazewell-Cary.[6]

The conclusion of the writers is that the two lateral moraines of Du Noir Valley represent two substages of the Wisconsin stage of glaciation, an early stage represented by the higher, Bull Lake moraine, probably Iowan and possibly the equivalent of Wisconsin I, and a later glaciation represented by the lower, Pinedale moraine, probably to be correlated with the Wisconsin II. These conclusions are based on the following observations. (*a*) the degree of weathering, even considering the climatic conditions, is surprisingly similar on the two moraines; (*b*) the general continuity of both moraines shows little evidence of erosional differences aside from the breaks in the Bull Lake in the valleys mentioned; (*c*) the amount of postglacial stream-cutting is far in excess of the cutting accomplished during the time intervening between the two stages of glaciation represented by the two moraines. Were the upper moraine Illinoian in age, the interval separating the two moraines should be greater than that of the interval separating the Pinedale stage from the present valley level.

GLACIAL HISTORY

The size of the cirques and their numbers, together with the extent of the lateral moraines, indicate clearly that the ice lobe extending down Du Noir Valley was much larger than that in the upper Wind River Valley. When Bull Lake ice moved down the Du Noir, the valley floor was probably some 150–200 feet

[3] *Ibid.*, p. 324. [4] *Ibid.*, p. 325.

[5] "Glacial Chronology of the Southern Rocky Mountains," *Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 1874–77.

[6] *Ibid.*, p. 1914.

higher than at present. Ice from East Fork and West Fork united high in the valley to form a large main mass moving down valley. The addition of other sizable glaciers from the east evidently exerted considerable crowding, causing lateral planation against the west side of Du Noir Valley and the accompanying oversteepening of that slope. Certainly Bull Lake ice spilled over into the valley

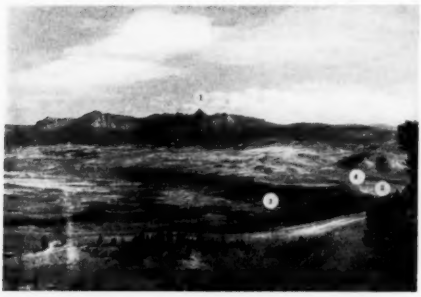

FIG. 4.—Mouth of the Du Noir Valley and the east wall along which the Bull Lake and Pinedale moraines extend. Bench Creek flows to the right of 4.

of Long Creek, as is evidenced by the glacially gouged gap in the vicinity of Dry Lakes (Fig. 2, 5) and the presence of Madison and Tensleep boulders directly traceable to the Upper Du Noir and Ramshorn Peak area (Fig. 4, 1). In some parts of the lower valley the Bull Lake glacier was two miles wide. It also occupied the lower valley of the present Bench Creek and apparently spilled over the narrow gap just below the juncture of the Wind River and Du Noir River (Fig. 4, 2). It also poured over the prominent spur on the west side of the valley just above the point of juncture. The general trend of the glacial debris from the mouth of Du Noir Valley across Wind River Valley may be readily traced by the Madison and Tensleep boulders. The Wind River glacier was carrying debris from Tertiary sediments and volcanics almost entirely.

Du Noir glacier thrust into Wind River Valley and apparently effectively blocked off Wind River glacier. Heaps of moraine extend up Wind River Valley from this junction to a point one mile upstream from the entrance of Long Creek into the Wind River Valley, a total distance of over two miles. Wind River today flows through this massive moraine, in reality a terminal moraine of the combined Wind River, Long Creek, and Du Noir glaciers.

Events which followed the Bull Lake stage can be postulated only upon the basis of what followed the Pinedale stage, for it is probable that similar conditions prevailed. A terrace level about 50 feet above the floor of the present valley, and upon which the highway up Du Noir Valley is built (Fig. 4, 3), seems to represent the post-Bull Lake Valley floor over which Pinedale ice advanced. The smaller size of its lateral moraine suggests that the Pinedale glacier persisted for a shorter time than the Bull Lake glacier. Ice advanced from the same area as previously, and at the entrances to Fourmile, Fivemile, and Sixmile creeks the Bull Lake moraine was broken. The Pinedale lateral moraine is bowed into the valley in each of these areas and is much broader than elsewhere. This has been interpreted as either a persistence of glacial advance from these tributaries with steep gradients after movement had slackened in the main valley, or the volume of ice from these valleys during maximum glaciation was sufficient to crowd the main glacier.

That Pinedale ice was confined to the valley throughout most of its length is evidenced by the largely undisturbed higher Bull Lake lateral moraine. In the last mile of the valley, however, ice must

have overridden the walls on both sides, since the Du Noir Pinedale moraine exists north of the spur jutting into Wind River Valley (Fig. 2, *6*).

The mouth of Du Noir Valley, and also of Wind River Valley as Du Noir enters it, was completely blocked by the combined terminal moraine of Wind River and Long Creek glaciers and Du Noir glacier. Lake silts on the floor and slopes of the valley up to within about a mile of East Fork record ponded water in Du Noir Valley to a depth of nearly 300 feet at the valley mouth. It persisted for some time, since 3 feet of lake silts veneer the valley floor and the Du Noir River meanders over this silt-covered lake bottom. Similar silts in the valley of Long Creek suggest a similar ponding in this area, also.

While Du Noir Lake persisted, drainage waters from Du Noir Valley spilled southwest into Long Creek Valley in the vicinity of Dry Lakes (Fig. 1, *6*), and at the same time spillways through the valley of Bench Creek (Fig. 4, *4*) and Wagon Gulch conducted waters into the lower Wind River Valley. Quantities of well-washed coarse gravel high on the valley side and extending to the Wind River Valley attest this drainage.

The combined Wind River and Du Noir waters eventually cut through the terminal moraine of both glaciers and re-established the main channel. In the process, Wind River was crowded southward against the southwest slope of its valley. This crowding developed a sharp re-entrant in the weak sandstone of the valley wall and developed a steep wall some 400 feet high.

It is probably during this stage that the narrow steep-walled canyon was cut through the Tensleep sandstone near the mouth of Bench Creek. The main highway, U.S. 287, from Dubois to Teton National Park, passes through this narrow gap.

REVIEWS

The Origin of the Carolina Bays. By DOUGLAS JOHNSON. ("Columbia Geomorphic Studies," No. 4.) New York: Columbia University Press, 1942. Pp. xi+341. $4.50.

A preliminary glance at the numerous excellent aerial photographs in Johnson's book will convince every reader that the Carolina Bays represent a new and most peculiar type of land form. The so-called "bays" are shallow basins, a few hundred feet to several miles in length, with beautifully rounded oval outlines defined in part by single or multiple sand ridges usually most strongly developed around the southeastern quadrants of the depressions. They occur by tens or hundreds of thousands on the sandy coastal lowlands of the Carolinas and adjacent states; the long axes of the ovals are oriented in a northwest-southeast direction over a vast area. The striking symmetry of individual bays, and their mutual relationships as seen on mosaics, will whet the appetite of the reader for an explanation of the origin of these curious features.

After a brief introductory description of the bays and the setting of the problem, Johnson proceeds to an analysis of earlier views regarding their origin, devoting four chapters to the theory that they are pits or craters formed by the infall of a great swarm of meteorites. Melton and Schriever, who first brought many of the peculiar characteristics of the bays to general attention, arrived at the meteor-crater hypothesis largely by elimination of normal terrestrial processes as adequate causes for the oval form, subparallel orientation, and other extraordinary features of the sand-rimmed depressions. Subsequent discovery of magnetic highs in some parts of the pitted plain has been interpreted as indicating the presence of buried meteoritic bodies, and the meteor-crater view, widely publicized because of its spectacular nature, has come to be widely accepted. Because of a lack of direct evidence that the South Atlantic coast was recently subjected to a veritable rain of meteorites larger in size than any known to science, and because, even if such an occurrence be accepted as a postulate, it would still fail to explain the extraordinary characteristics of the bays, Johnson regards the meteor-crater hypothesis as untenable.

The author calls his own theory the "hypothesis of complex origin," or, more fully, the "artesian-solution-lacustrine-aeolian hypothesis." He devotes one chapter to a statement of the theory, one to a demonstration of its competence to explain all the puzzling features of the bays, and one each to the further testing and analysis of the four phases of the hypothesis mentioned in its title. It will make for clarity in this review if attention is directed to Johnson's views regarding three outstanding questions that will spring to the mind of every reader: (1) the manner of origin of the depressions, (2) the reason for their northwest-southeast elongation and subparallel orientation, and (3) the manner of development of the rounded outlines and the origin of the sand rims.

1. The depressions are attributed chiefly to excavation by upward-moving artesian water and to removal by ground water and artesian water of soluble constituents of the subjacent sediments. The resulting basins were broad and shallow, contrasting in this respect with somewhat analogous sinks in soluble hard rock because of ready slumping of the relatively unconsolidated coastal-plain beds and a superficial mantle of loose sand. In so far as the depression-forming processes, as such, were concerned, the original forms may have varied widely in shape; it is worth noting, in this connection, that the typical oval bays are often associated with irregular, closed depressions, clearly the result of settling, and that every gradation between irregular and oval depressions occurs. Those depressions favorably situated with regard to the ground-water table at the time of their formation were occupied by shallow lakes.

2. The elongation of the depressions is ascribed (*a*) to slumping and outflow of quicksand from those portions of the margins of the basins where ground water entered the lakes, the "quickness" of the sand being due to exceedingly slow upward and outward currents of water; (*b*) to the solutional enlargement of a breach in a cap rock over an artesian aquifer, such enlargement tending to elongate the breach (and therefore the associated surface depression) up the direction of artesian flow; and (*c*) to a systematic shifting of points of emergence of upward-moving artesian water owing

to variations in the strength of artesian and ground-water movements.

The subparallel northwest-southeast orientation of the longer axes of the bays is held to be due to a relative constancy in the southeastward (downslope) direction of flow of ground water previous to a recent incision of streams and to a constancy in southeastward (downdip) direction of movement of artesian water.

3. The perfection of the oval outlines is ascribed in part to the tendency of saturated loose sand to flow uniformly toward a center of removal and in part to the work of waves and wave-generated currents during the lacustrine phase of development of the bays. This part of the hypothesis of complex origin merits special attention, because, while all geologists will agree that littoral processes tend to smooth shoreline irregularities, many will hesitate to credit to these processes the wonderfully systematic outlines that characterize the bays. The question is one of degree rather than of kind. But the evidence adduced to prove that the symmetric sand ridges that define the bay margins are shoreline features, and especially the fact that several more or less concentric ridges around multiple-rimmed bays show the same systematic symmetry, is wholly convincing. As a further test of the competence of shoreline processes to produce the forms in question, the reviewer sought maps of the Minnesota lake district and found there, now in process of formation in lakes of the same order of magnitude as the bay lakes, and in similar sandy materials, many of the features of the bay rims and many lakes which rival the bays in perfection of rounded and oval outlines.

Some of the bays still contain lakes, but the majority are floored by swamps or peaty soils. Johnson believes that the transformation was due to a general lowering of the water table and, in part, to the encroachment of vegetation. It occurs to the reviewer that study of the pollen spectra and the general microbiology of core samples of the lacustrine sediments might aid in dating the lake stage, but this problem must await the attention of properly qualified experts in these fields. The tendency for the sand rims to be stronger and broader around the southeastern quadrants of the bays is attributed to a dominance of westerly winds which caused a preferential eastward movement of sand by the waves and currents of the lakes and by wind directly during and after the close of the lacustrine stage.

The reader who prefers the type of theory in which each and every stage in the development of a given feature is ascribed to one, and only one, process, operating in a fixed manner at all times throughout a large area, may feel confused and somewhat resentful at the freedom with which Johnson presents several possible explanations of the same feature. A younger and less experienced investigator might feel obligated to "commit himself," and an investigator less "fertile in invention," never having been troubled by the alternative possibilities that lie beyond his ruling theory, might have discussed the origin of the Carolina Bays as though he had been on hand to watch every stage in their development. The fact is that many of the processes that entered into the formation of the bays are not now in operation in the bay area or operate at the present time with greatly reduced vigor; some of the formative processes that may still be in operation are not susceptible to direct observation because they are subterranean. Having gathered together every shred of available evidence and subjected each of many lines of thought to rigorous analysis, Johnson finds himself with some processes that are certainly solely responsible for some features of the bays (such as the final smoothing of their outlines by wave work); with some processes that certainly operated locally but which cannot be given exclusive credit for the development of certain features because other processes, competent to produce similar forms, cannot be eliminated by available evidence (such as the role of solution in the formation of the depressions); and with some processes that may or may not have contributed to the development of certain features and whose quantitative importance is not assessable (such as the migration of a breach in a subsurface cap rock in the elongation of the bays). The strength of his discussion lies in the precision with which each line of thought is stated for exactly what it seems to him to be worth, together with a clear statement of the evidence, postulates, and reasoning on which his judgment is based. Without agreeing as to the relative quantitative importance of each of the processes described, the reviewer finds in the hypothesis of complex origin a complete and definitive solution of the perplexing problem of the origin of the bays.

Johnson's protracted researches on the bays problem resulted in the accumulation of an immense mass of detailed observational data of many types and involved consideration of a wide variety of processes, some far afield from geology. His success in organizing this material

for an audience that will include geologists, scientists in other fields, and intelligent laymen is a tribute to his mastery of the art of presentation. The volume will reveal to the lay reader the full meaning and utility of the scientific method by providing a fascinating record of its application in an attack on a complex problem; the scientist will find in it an ingenious and fully documented explanation of a new and extraordinary type of land form.

J. HOOVER MACKIN

The Dynamics of Faulting and Dyke Formation with Application to Britain. By E. M. ANDERSON. Edinburgh: Oliver & Boyd, 1942. Pp. 191; figs. 38. 15*s.* net.

The author considers three classes of faults: (1) thrusts in which the greatest pressure was horizontal and the least pressure was vertical; (2) "transcurrent" faults where both the greatest pressure and the easiest relief were horizontal; and (3) normal faults in which the greatest pressure acted vertically and the easiest relief (reduced pressure or tension) was horizontal. Each type is illustrated by a group of three diagrams showing (*a*) the greatest, intermediate, and least axes of stress, (*b*) the planes of maximum tangential stress relative to the axis of greatest pressure, and (*c*) the planes of actual faulting. In all cases the faulting is at a more acute angle with the greatest pressure than the 45° planes of maximum shearing stress, in accordance with what the author calls "Navier's principle" (Paris, 1833), or what geologists in this country have sometimes called "Hartmann's law" (Paris, 1896). Navier has priority by half a century, and his principle has been adopted by Anderson as the chief basis for his analysis of the faulting in Britain. And, in turn, the results of this study are regarded by the author as a vindication of that principle.

Anderson says: "Dykes are strictly tension fractures, although, as was seen in the last chapter, they must have arisen from depths at which the tension cannot be regional" (p. 28). For upward advance from such depths he pictures the dike tapering to a sharp edge which splits and wedges apart the rock ahead of it by the magma's superior hydrostatic pressure. He argues "from the close connection which subsists between dykes and normal faults, that the conditions are usually the same." It would seem to the reviewer, however, that not enough attention is paid to dikes which follow older lines of fracture developed under stress conditions quite different from those obtaining when the intrusion took place.

Utilizing his concepts of faulting and dike intrusion, the author classifies the major fault and dike systems of Britain and postulates the orientation of the causal stresses. For each episode of major deformation the crustal stresses are found to have affected large areas, and doubt is cast on the importance of local variations. Areal variations of rock resistance, however, are factors seemingly not to be overlooked.

Impressing the reader particularly is the wide prevalence and magnitude of essentially vertical faults with dominantly horizontal slip. Many of the greatest faults in Britain are of this type, for which the author has adopted the designation "transcurrent faults." The term, however, does not seem a happy one because "running across" something is not the significant characteristic of many of these faults, although in other cases (as across the folded Juras) it very obviously is. The name "strike-slip fault" is cumbersome. The reviewer wonders whether the term "trace fault" would have sufficient advantage to warrant its introduction. This could be used for a fault whose dominant component of slip was parallel to the trace of the fault as it appears on a map.

Probably some geologists will regard this analysis of faulting and its application as an oversimplification, because various modifying factors are not sufficiently considered. For example, Navier's principle applies particularly to brittle materials fractured in crushing machines where rupture occurs with but little preliminary plastic distortion. But in the earth important yielding by rock flow very commonly precedes fault-rupturing, in which case the inclination of the faults may be quite different from what the Navier principle might lead one to expect. We know that differences in rock competency mean differences in behavior under stress, and the strains may be either rotational or nonrotational. Navier's principle is only one of several principles involved. But perhaps, with present information, some such simplification is a practical necessity. In any case structural geologists will be thankful to have the results of this study, which are distinctly valuable.

R. T. C.

"Laterite and Its Structural Uses in Thailand and Cambodia." By ROBERT L. PENDLETON. (*Geographical Review*, Vol. XXXI.) New York, 1941. Pp. 177–202; figs. 63.

"Laterite, or Sila Laeng, a Peculiar Soil Formation." By ROBERT L. PENDLETON. (*Thai Science Bulletin*, Vol. III, Nos. 3–4.) Bangkok, 1942. Pp. 61–77; pls. 24.

"Analyses and Profile Notes of Some Laterite Soils and Soils with Iron Concretions of Thailand." By ROBERT L. PENDLETON and SANGAR SHARASUVANA. (*Soil Science*, Vol. LIV.) Baltimore, 1942. Pp. 1–26; figs. 8.

In 1807 Francis Buchanan proposed the term "laterite" for a ferruginous material which was quarried from the soil of south India in blocks which hardened upon drying and could then be used in the construction of masonry buildings. Since Buchanan's time the word "laterite" has been applied to several different soil and subsoil materials in equatorial regions. The demonstration by Max Bauer in 1898[1] that laterite from the Seychelles Islands was made up essentially of iron and aluminum hydroxides has influenced most geologists who have proposed definitions since that time. Now Pendleton, as the result of his extensive field experience in Thailand, concludes that the varied bulk composition of Thai laterites and their frequently close association with aluminum-silicate clays make desirable a return to Buchanan's usage. "Laterite" would then become a soil term, and its definition would be based on characters determinable in the field.

Pendleton's usage is similar to that of E. C. J. Mohr, of the Netherlands Indies, and J. A. Prescott, of Australia, and not greatly different from that of J. B. Scrivenor[2] and several other men with tropical field experience. Pendleton has been influenced especially by Mohr.

In Thailand and adjacent Cambodia laterite has been used extensively as a building stone, especially in the great structures of the tenth and eleventh centuries. It is still quarried and used to a small extent. A good idea of the ancient ruins and of the appearance of laterite blocks can be obtained from the numerous fine illustrations in Pendleton's article in the *Geographical Review*.

Laterite is widespread in Thailand as a subsoil layer formed beneath an extensive peneplain and characterized essentially by the presence of an abundant iron-oxide cement. The laterite layer is usually between $\frac{1}{4}$ and 4 meters in thickness and covered by 1 meter or less of leached surface soil (lixivium). The laterite horizon may be a rather soft, but continuous, mass suitable for quarrying, or made up of discontinuous limonotic chunks or pellets. Laterite is almost never formed at the surface; extensive exposures are due to the removal of the overlying soil.

The surface soil above laterite is commonly either clay or a quartz-rich sand. The laterite is pisolitic if developed in a soil derived from sandstone; if developed in a clay soil it encloses blebs of the clay and later may become vesicular if the clay is washed away during erosion. The associated clay has the physical properties of an aluminum silicate rather than a hydroxide or oxide, and analyses of clay ("fine earth") developed on andesite (?) run 40–42 per cent SiO_2.[3] One set of laterite chunks suspected of a basaltic origin ran 6.2 per cent SiO_2, 62.5 per cent Fe_2O_3, 15.9 per cent Al_2O_3.[4] More commonly, the hard laterite contains a percentage of sesquioxides two to four times that of silica; for the fine earth the reverse is frequently true.

As Pendleton points out, it would be desirable to have analyses and X-ray studies of colloids from the Thailand clays associated with laterites. The petrologist, especially, feels the need of such studies, and also of petrographic work, in order to show just what aluminum and iron minerals are present, and the texture (in the petrologic sense) of the indurated soil material. But, whatever may be the details and variations of laterite composition, Pendleton has made a persuasive argument for a return to Buchanan's definition. The word is needed as a field term by workers in equatorial regions.

The reviewer, accepting "laterite" as a general field term, feels the need of another word for weathered material which is found by laboratory study to be composed essentially of aluminum hydrates, with or without iron hydrates. For this purpose "allite" is available.[5]

A. O. WOODFORD

Report of a Conference on Sedimentation. Tulsa: American Association of Petroleum Geologists, 1942. Pp. 68 (planographed).

This publication is a transcript of the proceedings of a conference conducted by the Research Committee of the Association at Denver,

[1] *Neues Jahrbuch*, II, 193.

[2] *Geology of Malaya* (1931).

[3] Pendleton and Sharasuvana, p. 12.

[4] *Ibid.*

[5] H. Harrassowitz, *Fortschr. d. Geol. u. Pal.*, Vol. IV (1926), p. 255.

Colorado, on April 25, 1942. A. I. Levorsen presided. The meeting, which purported to be a round-table discussion on the nature and content of college courses on "sedimentation," apparently developed into a debate on the value of the quantitative approach to the problems of the sedimentary rocks.

Formal papers were presented by W. H. Twenhofel, of the University of Wisconsin, R. Dana Russell, of Louisiana State University, P. D. Krynine, of Pennsylvania State College, and W. C. Krumbein, of the University of Chicago. The report also contains a verbatim record of the discussion of others engaged in the teaching of sedimentation and by petroleum geologists. In all, twenty-seven individuals participated.

The report will be of value as a summarization of the present views and philosophies of those engaged in both teaching and research in the field of sedimentology. It contains many fruitful suggestions and outlines the shape of things to come in this rapidly growing phase of geology. It contains also helpful discussion on the ways in which a student can be better fitted for petroleum geology, which means in the last analysis a better geologist.

F. J. PETTIJOHN

The Geology of Crater Lake National Park, Oregon, with a Reconnaissance of the Cascade Range Southward to Mount Shasta. By HOWEL WILLIAMS. Carnegie Institution of Washington Publication 540. Washington, 1942. Quarto, pp. vi+162; pls. 31; figs. 31. Paper, $2.50; cloth, $3.50.

Recently reviewed in the *Journal*[1] was *Crater Lake: The Story of Its Origin*, by Howel Williams. This was a delightful, semipopular book of much scientific merit. Now, under the auspices of the Carnegie Institution of Washington, the same author has brought out what is in effect a monograph on the same subject. Whereas the earlier simplified version utilized only the evidence necessary to give the gist of the story of Crater Lake, the present volume sets forth in detail the full results of a comprehensive investigation which seemingly leaves little to be added by further work.

The air of mystery which has hung over Crater Lake has now been largely dispelled. Of the 17 cubic miles of former Mount Mazama which have been removed to form the present caldera, only about 1½ cubic miles of the cone were blasted away by explosion. An additional 5 cubic miles of pumice and scoria, derived from new magma, were scattered over the surrounding country, in place of which a comparable volume of old rock could have caved into the magma chamber. The remaining 10½ cubic miles of the old volcano must have vanished by collapse and engulfment following withdrawal of magmatic support as large volumes of magma were injected into fissures at depth.

R. T. C.

[1] No. 2 (1942), pp. 220–21.

A book of 119 magnificent aerial photographs

FLIGHTS OVER ANCIENT CITIES OF IRAN

By ERICH F. SCHMIDT

"The reviewer has seen no other publication in which air photographs have been so sumptuously presented. The large format permits a magnificent sweep of landscape in full-page views. The archeologist and the historian will delight in the details so clearly shown in the pictures themselves and further elucidated in the text and by means of supplementary maps, transparencies, and lines drawn on some of the views themselves to emphasize particular features. The text is a pleasant blending of archeology with informal accounts of flights and journeys. Many of the oblique views are breath-taking in the austere grandeur of the desolate scenery they show, especially in the little-known mountains of Fars and Luristan and along the fringes of the desert. . . . . Many of the photographs will interest geographical students of land forms and erosion patterns as well as of types of contemporary settlement and land utilization. . . . ."—*Geographical Review.*

119 plates, 6 maps, folio (30×40 cm.)

$20

SPECIAL PUBLICATION OF THE ORIENTAL INSTITUTE OF THE UNIVERSITY OF CHICAGO

The UNIVERSITY *of* CHICAGO PRESS

Among the articles to appear in early numbers of *The Journal of Geology* are the following:

Critical Structures of the Gros Ventre and Northern Hoback Ranges, Wyoming. By VINCENT E. NELSON and VICTOR CHURCH

Flow Structures in the Berea Sandstone and Bedford Shale of Central Ohio. By JOHN R. COOPER

Some Altered Palagonite Tuffs from Jamaica and the Origin and History of Their Chlorites. By FRANK RAW

The Rarer Metallic Constituents of Some American Igneous Rocks, II. By ERNEST B. SANDELL and SAMUEL S. GOLDICH

Reference List in Earth Sciences. By LINCOLN R. THIESMEYER

An A.A.P.G. Book (1942)

SOURCE BEDS OF PETROLEUM

By PARKER D. TRASK and H. WHITMAN PATNODE

REPORT OF INVESTIGATION SUPPORTED JOINTLY BY THE AMERICAN PETROLEUM INSTITUTE AND THE GEOLOGICAL SURVEY OF THE UNITED STATES DEPARTMENT OF THE INTERIOR FROM 1931 TO 1941

RESULTS OF A.P.I. RESEARCH COMMITTEE NO. 4. WORK DONE UNDER ADVISORY COMMITTEE COMPOSED OF R. F. BAKER, B. B. COX, F. B. CLARK, K. C. HEALD, W. B. HEROY, L. P. GARRETT, F. H. LAHEE, A. W. McCOY, H. D. MISER R. D. REED, AND L. C. SNIDER

"The main object of this study of lithified deposits has been to determine diagnostic criteria for recognizing source beds."

600 pages, with bibliographies and index.
72 figures, 152 tables. 6 x 9 inches.

$4.50, POSTPAID
($3.50 to *A.A.P.G. members and associate members*)

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
Box 979, Tulsa, Oklahoma, U.S.A.

A DESCRIPTIVE PETROGRAPHY OF THE IGNEOUS ROCKS

By Albert Johannsen

Volume I. INTRODUCTION, TEXTURES, CLASSIFICATIONS, AND GLOSSARY $4.50

Volume II. THE QUARTZ-BEARING ROCKS $4.50

Volume III. THE INTERMEDIATE ROCKS $4.50

Volume IV. Part I. THE FELDSPATHOID ROCKS

Part II. THE PERIDOTITES AND PEGMATITES $4.50

"Petrographers will be extremely grateful to Prof. Johannsen for assembling this valuable material which they can and will use. . . . . The writing is exact, lucid, scholarly, and . . . . is a pleasure to read and handle."—*Science Progress* (England)

The University of Chicago Press